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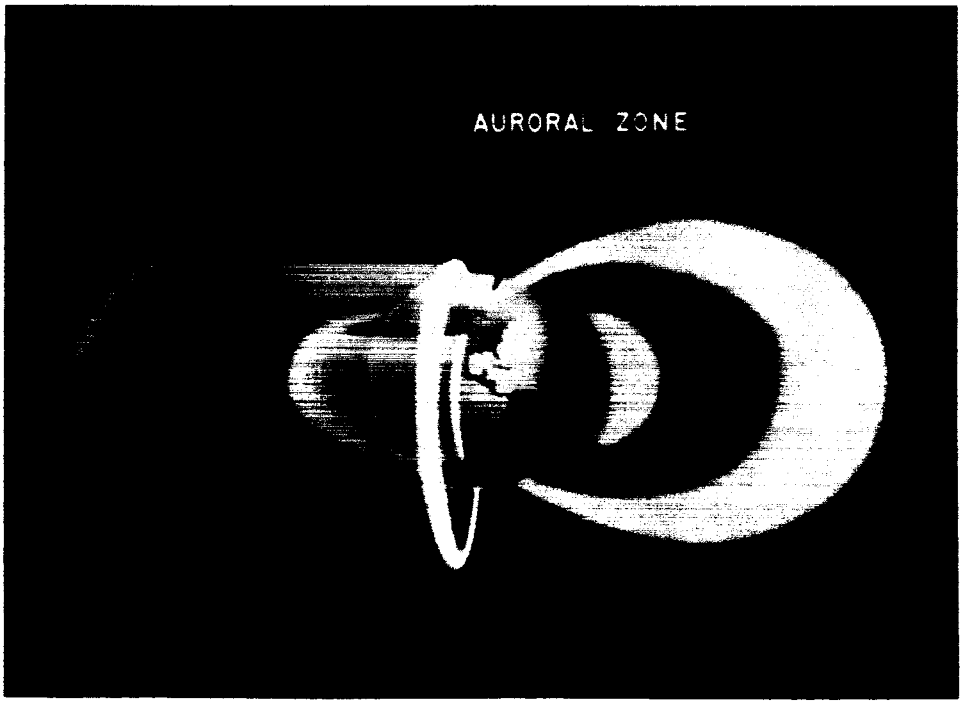
Results of Experiments in Space

BY ROBERT JASTROW

Director, Institute for Space Studies
Goddard Space Flight Center



See page 18

Presented as the 25th Wright Brothers Lecture for the Institute of Aerospace Sciences, Washington, D.C., December 18, 1961

The Wright Brothers Lectures of the Institute of Aerospace Sciences

The Wright Brothers Lecture is delivered annually, in Washington, D.C., on December 17, the anniversary of the first powered flights by Orville and Wilbur Wright at Kitty Hawk, North Carolina, in 1903.

The Lecturer chosen is a person of great distinction in the aerospace sciences, and selection as Lecturer is one of the most significant honors bestowed by the Institute of Aerospace Sciences. The Lecture is endowed by the Vernon Lynch Fund.

In past years, the Lecturers have been:

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1941	Richard V. Southwell	1953	Glenn L. Martin
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CONTENTS

ROBERT JASTROW

DIRECTOR

Institute for Space Studies
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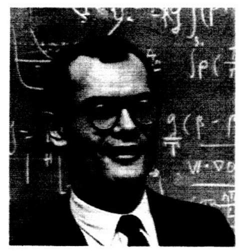

Dr. Jastrow was born in New York, N.Y., on September 7, 1925. He received an A.B. from Columbia College in 1944, an A.M. from Columbia University in 1945, and a Ph. D. in theoretical physics from Columbia University in 1948. His research experience has been in the fields of nuclear physics and upper atmosphere physics.

During the period between 1948 and 1954, Dr. Jastrow was a postdoctoral fellow at Leiden University in The Netherlands, a member of the Institute for Advanced Study in Princeton, and a research associate at the University of California. He also taught physics at Columbia, Yale, and Cooper Union. From 1954 to 1958 he served as a consultant in nuclear physics to the U.S. Naval Research Laboratory in Washington. He is currently Chief of the Theoretical Division and Director of the Institute for Space Studies, Goddard Space Flight Center, National Aeronautics and Space Administration, and also Adjunct Professor of Geology at Columbia University.

Dr. Jastrow served as Chairman of the Lunar Science Committee in the NASA Office of Space Flight Programs during 1959–60. He is Secretary of the Planning Committee on Planetary Science of the American Geophysical Union, and a member of the Rocket and Satellite Research Panel, the Space Science Board Committee on the Ionospheres of Earth and Planets, and the IUGG Committee on the High Atmosphere. He is also co-editor of the JOURNAL OF ATMOSPHERIC SCIENCES.

Dr. Jastrow is a fellow of the American Physical Society and the American Astronautical Society, and a member of the Physical Society (of Great Britain), the Royal Astronomical Society, the American Astronomical Society, and the American Geophysical Union.

Results of Experiments in Space

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Director, Institute for Space Studies
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U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON : 1962

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C. - Price 25 cents

RESULTS OF EXPERIMENTS IN SPACE

It is a deeply appreciated honor to be invited to speak on this occasion commemorating a great event in the history of our efforts to travel through the atmosphere. The accelerating pace of advances in controlling and exploring our environment hardly leaves time for reflection; and it is extraordinary that only 58 years after the first flight of the Wright Brothers we should already be embarked on major projects aimed at giving us, at an early date, the ability to travel beyond the atmosphere and out into the solar system.

My own involvement in the space program has been limited to the special projects concerned with the application of space flight vehicles to basic scientific problems, and I shall today review some of the major accomplishments in that field during the past several years.

Experiments in space have yielded a phenomenal amount of new information regarding the physical processes which govern our environment, and in this general review it is necessary to be selective in choosing a few central problems, to the exclusion of many other important developments which might be included in a fuller discussion.

These scientific applications of space flight vehicles are a small part of the program, and cost relatively little, but they are extremely important, because out of them come the advances in our understanding of the basic physical laws which mold our environment—an understanding on which our lives are based to a large degree, and on which our future achievements will depend.

What are the major lines of scientific inquiry in the space program, and problems which provide the basic motivation for space science experiments? In the physical sciences these basic problems of space science include a broad area, cutting across the traditional boundaries of astronomy, physics and the earth sciences, but are grouped around the following three central questions:

the structure of stars and galaxies: stellar evolution, nucleosynthesis, and the cosmic abundances of the elements;

the origin and evolution of the solar system: the formation of the sun, and the early histories and present structures of the planets;

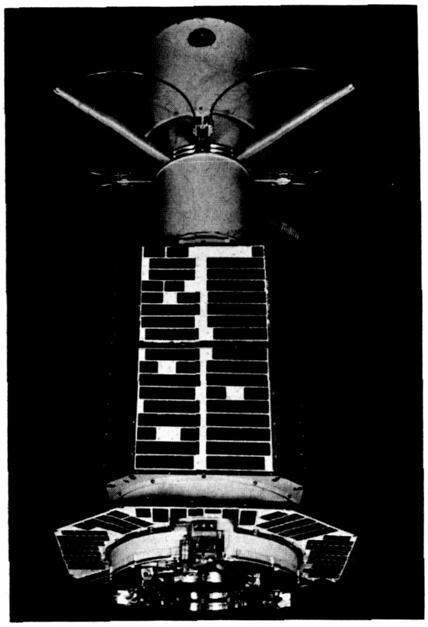
solar control over the atmosphere of the earth: the causes of weather activity in the lower atmosphere, and the structure of the upper atmosphere.

Among these three major lines of inquiry, the contribution of the space program to the first two is largely potential; its promise for the future rests on projects now under development but not yet completed, and the preliminary accomplishments in these two fields can be quickly reviewed.

The third area has been greatly stimulated by the rocket and satellite projects of the IGY and the first years of the space program, and has already seen great activity. It is one of the most exiciting and fruitful fields of research in the space science program, and I shall therefore discuss it at greater length.

Rocket and Satellite Astronomy

The first set of problems, relating to the structure and evolution of stars and galaxies, concerns the manner in which stars are born by condensation out of the gas and dust of interstellar space; the manufacture of the heavier elements out of hydrogen by nuclear fusion within the star, a process which occupies the greater part of the life of the star; and the terminal phase in the life of the star, ending either in the white dwarf stage or in final destruction by a supernova explosion.



EXPLORER XI—This highly sophisticated gamma ray astronomy satellite was launched by a four-stage Juno II vehicle. It was designed to locate the sources of gamma radiation in outer space.

This picture of the genesis and evolution of stars has been gained through the spectroscopic analysis of light emitted from the stars and received by telescopes on the ground.

In fact, all our information on the nature of the universe outside our solar system is obtained by the examination of stellar radiation transmitted through our atmosphere and collected by surface telescopes. Yet the fraction of this information which gets through the atmosphere is extremely small; it comprises only the very narrow band in the visible, and a part of the radio region. The atmosphere filters out all the information which we could otherwise obtain from the ultraviolet, the x-rays, gamma rays, and large parts of the infrared and radio regions.

With the aid of rockets and satellites we can for the first time extend our observations across the full spectrum by placing a telescope in orbit above the atmosphere, thereby gaining access to previously denied knowledge regarding the universe. This potential achievement of the orbiting telescope represents one of the most important contributions which space research can make to basic science. The development of the orbiting telescope is well along, but the flights actually achieved thus far involve only preliminary instruments. In rocket astronomy the first stellar ultraviolet spectrum has been obtained by James E. Milligan and Theodore P. Stecher of the Goddard Space Flight Center. Rocket flights have also yielded ray intensities, obtained by Herbert Friedman, Talbot A. Chubb, Robert W. Kreplin, and Richard L. Blake at the Naval Research Laboratory; and the ultraviolet spectrum of the sun, measured by Richard Tousey, David L. Garrett, and James D. Purcell of the Naval Research Laboratory, by W. E. Rense of the University of Colorado and by Hans E. Hinteregger of the Air Force Research Division.

The measurements by Hinteregger yield the absolute intensity of solar ultraviolet radiation. They play a critical role in atmospheric physics, and I shall return to them later.

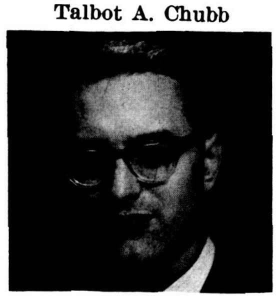
In satellite astronomy the NRL group has studied solar x-ray and Lyman Alpha radiation. They find a strong enhancement of x-radiation during flares, but no change in the Lyman Alpha line. Another achievement which warrants mention, although it, too, is a preliminary experiment, is the gamma-ray telescope developed by Kraushaar and Clark of MIT, which was designed to locate the sources of energetic radiation in outer space, and was launched by Goddard as the Explorer XI satellite. The data yielded by this instrument are not yet completely analyzed, but the preliminary results are already of interest in that the measured level of gamma radiation rules out one version of the steady state cosmology, according to which matter and anti-matter are created simultaneously. If this version were correct, and matter and anti-matter were created at the rate required in the steady state theory, the intensity of gamma rays produced in outer space by their annihilation would be 1,000 times greater than the level measured by Kraushaar and Clark.

Origin of the Moon and Planets

We turn next to the problems associated with the origin of the solar system and the development of planetary bodies. Two major branches of science are united in the study of this problem: astrophysics, in the consideration of processes at-

James D. Purcell

Talbot A. Chubb



tendant on the development of the primitive sun and the formation of the surrounding sola nebula; and geophysics, in the attempt to deduce the early histories of the planets from their present structures. This effort to roll back the history of 4.5 billion years, and to unravel the tangled complex of physical and chemical processes accompanying the birth of the planets, is in my view one of the most interesting problems in modern science.

In the investigation of this set of questions the physical exploration of the moon and the planets by unmanned and manned spacecraft will play a unique role, in providing us with our first opportunity for a comparative study of the structures of the planets; and the moon in particular should yield information of exceptional interest, because its surface is likely to have preserved a record of past events going back billions of years, unmarred by the erosive effects of atmospheres and oceans, and relatively unchanged by mountain-building processes. This is a record lost on the earth, probably lost on Mars and Venus, and probably available nowhere else in the solar system on a relatively accessible body.

A thorough exploration of the moon and the planets is some years off, but preliminary explorations of the moon are planned to start next year in the U.S. program, and the USSR has already achieved a result of great importance in the circumlunar flight of Lunik III, by which the first images of the moon's hidden face were secured.

BACK OF MOON—Photograph of the hidden side of the moon taken by Lunik III. The markings indicate special surface features noted by Soviet astronomers. The following names have been suggested by the USSR for some of these markings: (1) The Sea of Moscow; (4) Lomonosov, a crater with a central peak; (7) The Soviet Mountains. The Roman numerals denote objects at the edge of the photograph which are also visible from the earth. Some of these are: (I) The Sea of Humboldt; (II) The Sea of Crisis; (VI) The Sea of Fertility. (Pictures and diagram of Lunik III on page 4.)

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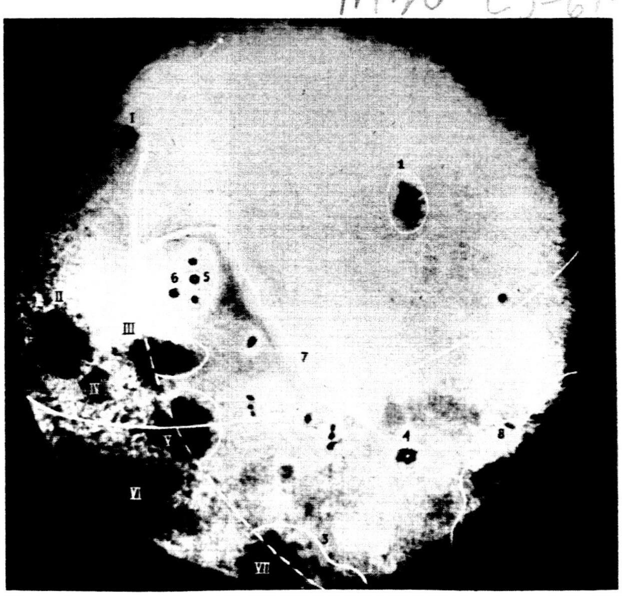
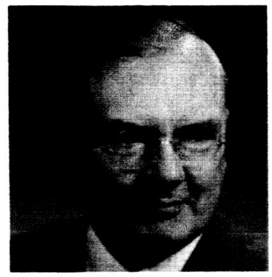


John O'Keefe

Herbert Friedman



Richard Tousey

Richard L. Blake

David L. Garrett

William A. Rense

H. E. Hinteregger

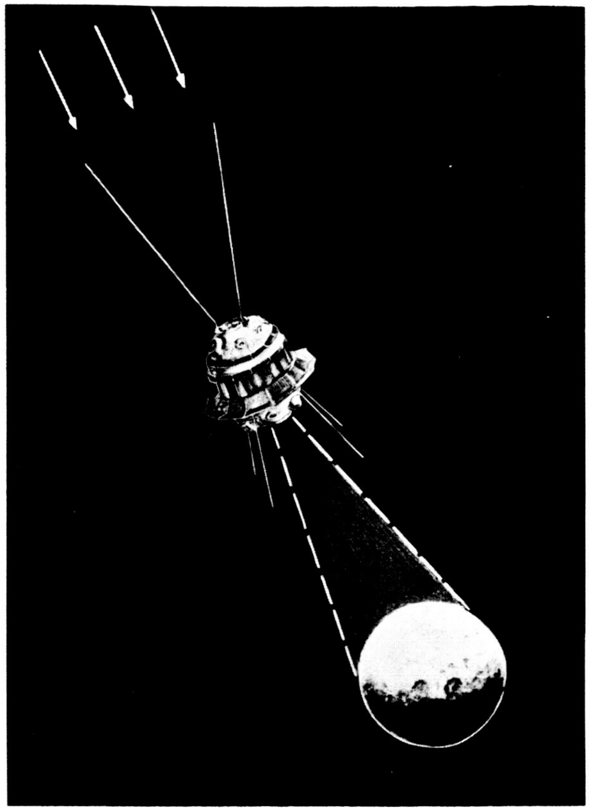
Robert W. Kreplin

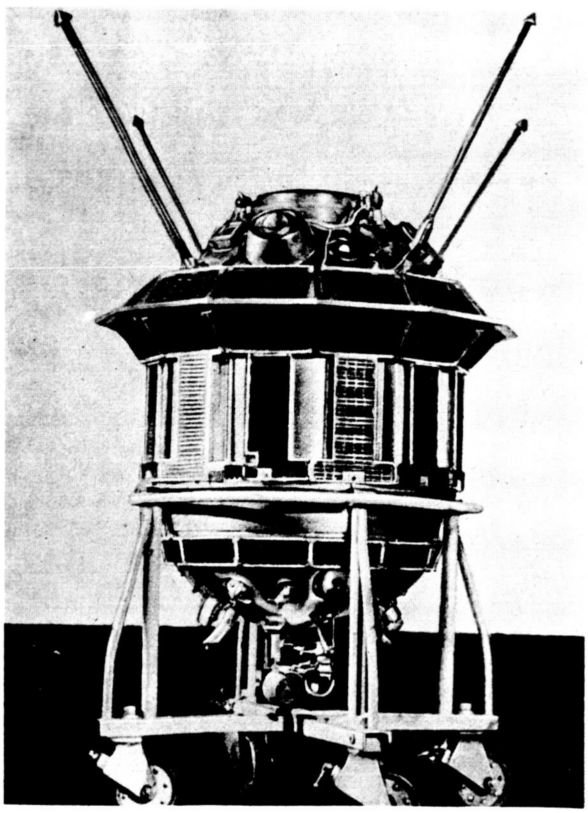
LUNIK III

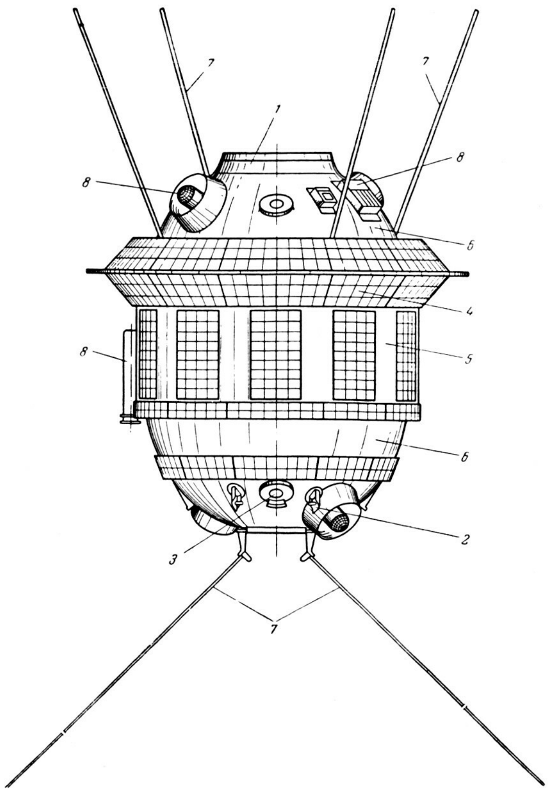
Right: Position of the Automatic Interplanetary Station in space when photographing the other side of the moon. The arrows show the direction of the Sun's rays.

Lower left: The Automatic Interplanetary Station, photographed on its movable carriage.

Lower right: Diagram showing the general appearance of the Automatic Interplanetary Station: (1) Illuminator for photographic apparatus; (2) orientation system motor; (3) solar orientation unit; (4) solar battery units; (5) heat control screens; (6) heat shields; (7) aerials; (8) scientific apparatus.







In spite of some blurring of the photographs they are still of great interest, for it is possible to distinguish on them a large number of features resembling the craters and maria on the front face. Perhaps the most interesting feature is the Soviet Mountain Range, a chain extending across the center of the moon's hidden face. The Soviet Range resembles the great ranges on the earth; it does not look like the formations characteristic of the mountains on the front face of the moon, which seem to be circular crater walls and deposits of debris formed by the impact of large meteorites on the lunar surface.

According to our present ideas, terrestrial mountains result from the combined effects of erosion and the wrinkling of the earth's crust produced by the slow shrinkage of our planet. The current consensus is that these mountain-building forces have been much less effective on the moon. The markings referred to as the Soviet Mountains could have resulted from the running together of several obscured but independent markings; but we may have to revise our theories of lunar structure if they continue to appear as a single range in later and more detailed pictures.

The second Soviet moon rocket, Lunik II, yielded one other item of great potential interest regarding the moon's structure.

This is a measurement of magnetic fields in the vicinity of the moon up to the time of impact on the lunar surface. From the Lunik II magnetometer data Soviet scientists concluded that an upper limit of approximately 100 gammas could be placed on the moon's magnetic field. The improvements on this limiting value which may be expected in future flights will be of great interest, because on the earth the magnetic field is supposed to be associated with currents in the liquid core of the planet, and the magnitude of the moon's magnetic field may therefore provide information on the presence or absence of a core within that body, which could in turn have a bearing on our understanding of the manner of formation of the moon and other similar bodies in the solar system.

Interior of the Earth

In regard to the general problems of planetary structure and history, we may expect to see major advances resulting from the coming explorations of the Moon, Mars, and Venus, but serious studies in this field are still some years off. However, in the present program there have already been important results achieved in determining the internal structure of our own planet, with the aid of near-earth satellites.

This somewhat paradoxical circumstance, in which knowledge of the interior of a planet is derived from the study of a body circling far above its surface, has the following explanation: A satellite moves in its orbit under the attraction of gravity, and the precise shape of its orbit is determined by the detailed nature of the gravitational field. The gravitational field depends on the distribution of mass, and this in turn reflects the internal structure of the planet.

To a high degree of approximation the earth has a spherical shape, and attracts the satellite with the gravitational force of a single point of mass located at the earth's center of gravity. Under the attraction of this mass point the satellite moves in an ellipse whose plane keeps a constant direction in space.

Actually the spherical shape is flattened at the poles, and bulges somewhat at the equator, under the influence of the centrifugal force produced by the rotation of the earth on its axis every 24 hours. If the earth is relatively plastic, as may be expected under the conditions of high temperature and pressure prevailing within its interior, then we may make a very precise calculation of the height of the bulge at the equator. The equatorial bulge is usually expressed in these calculations in terms of the fractional difference between the polar and equatorial radii, which is referred to as the flattening ratio. The calculations based on the assumption of a plastic earth yield a flattening ratio of 1/299.8, which corresponds to an equatorial bulge of about 21 km. This equatorial bulge produces an easily discernible effect on the satellite orbit, because it exerts an additional force of attraction on the satellite each time it passes over the equator, pulling the trajectory out of line to a slight degree on every pass, and causing the plane of the orbit to rotate slowly in space at a rate which depends on the size of the equatorial bulge. The rate of rotation of the plane of the orbit can be measured with high accuracy by the analysis of the tracking data. Studies of the orbital rotation rates of a number of satellites have, in this way, yielded a very precise value for the height of the equatorial bulge.

In this country the analyses of the orbital rotation and the equatorial bulge have been carried out largely by John A. O'Keefe, William M.

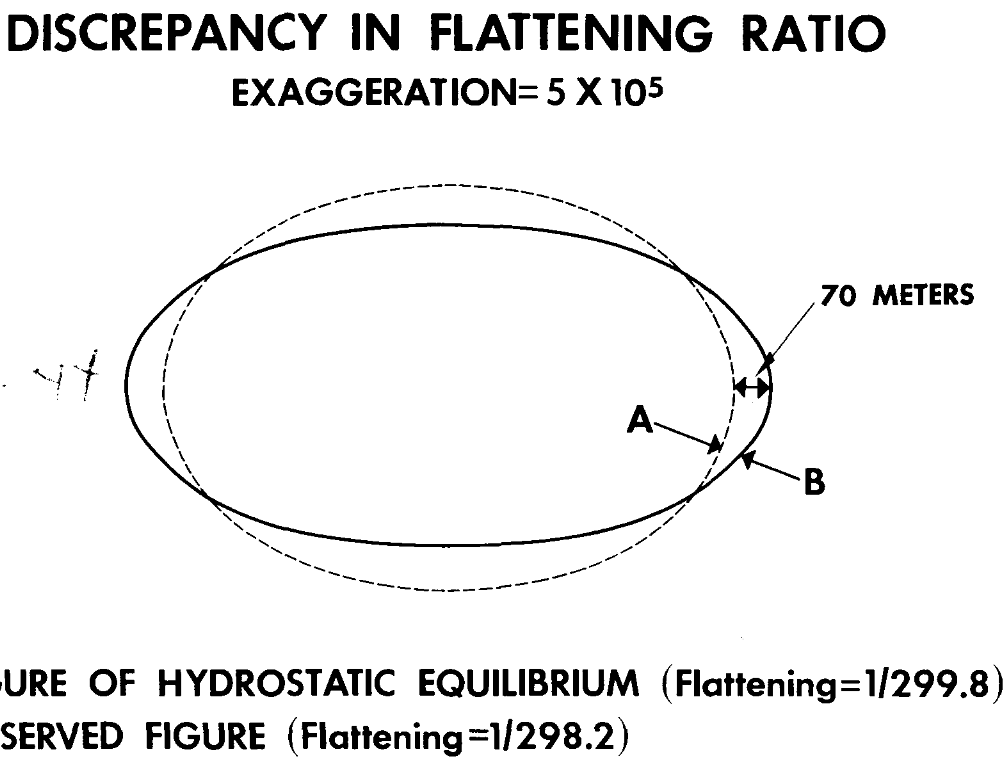


FIGURE 1. Shape of the earth: the discrepancy in the flattening ratio.

Kaula, and their associates of the Goddard Space Flight Center, by Yoshihide Kozai at the Smithsonian Astrophysical Observatory, and most recently by Robert R. Newton at the Johns Hopkins Applied Physics Laboratory. Their results indicate a flattening ratio of $1/(298.2 \pm 0.2)$.

Thus there is a discrepancy between the observed value of the flattening and the value obtained on the assumption of hydrostatic equilibrium. This discrepancy shown in exaggerated degree in figure 1, is substantially greater than the probable error in the observations, and indicates that the interior of the earth is not in hydrostatic equilibrium. It appears that the earth is not plastic, but has instead a mechanical strength within its interior, sufficient to maintain its shape, in spite of the stresses at the base of the mantle which must be associated with the departure from the figure of hydrostatic equilibrium. O'Keefe has estimated that a mechanical strength of 2×10^7 dynes/cm^2 would be required to support these stresses at the base of the mantle.

These results on the figure of the earth carry interesting implications regarding its history. The rate of rotation of the earth is steadily decreasing as a result of the effects produced by lunar tides. The pull of the moon on the earth raises tides in the seas, with amplitudes of many feet, as well as smaller tides in the mantle of the earth, with amplitudes of a few inches at the earth's surface. The dissipation of energy in the friction produced by these tidal motions gradually slows down the earth in its rotation. The current rate of change of the length of the day is about 10^{-3} sec per century. From this value we can calculate that the observed value of the flattening, as deduced from the Vanguard I data, would correspond to the figure of hydrostatic equilibrium for a plastic earth some tens of millions of years ago, when the day was about 23 hours and 30 minutes in length. Thus it appears that the mantle is sufficiently warm and plastic to respond to the changing stresses associated with the slowing down of the earth; yet it has enough internal strength to cause the response to lag behind current conditions by about 50 million years.

There are other departures of the geoid from the shape of hydrostatic equilibrium, in addition to the discrepancy in the flattening. These departures, which have also been determined primarily from the analysis of the Vanguard I orbit, include the famous pear-shaped component, or third harmonic in the expansion of the gravitational field. They also include harmonics of the fourth and fifth order. Higher harmonics than the fifth are lost in the noise level of the orbit determinations, within the accuracy of present tracking systems. The magnitudes of the undulations in the geoid, i.e., the departures from the figure of hydrostatic equilibrium, are shown in figure 2 for the third through the fifth harmonics. These undulations, which range between a few meters and a few tens of meters, seem insignificant in comparison with the radius of the earth, or even in comparison with the topographic irregularities on the surface. Nonetheless, they are of very great significance to the student of the earth's interior, because they represent actual variations in the gravitational field, which are related to the entire distribution of mass within the planet, and therefore have much more significance than topographic variations of the mass distribution at the surface alone. The third harmonic, for example, has an amplitude of 17 meters at the North Pole, and this means that there is an excess of mass under the North Pole, or some other more complicated variation of the mass distribution in the mantle, which is sufficient to draw up the level of the sea by 17 meters over an area comparable with the size of the Atlantic Ocean.

VANGUARD PROGRAM—A series of 14 were tested at the Atlantic Missile Range, Cape Canaveral, Florida. Seven were launches designed to place a scientific earth satellite into orbit as part of the U.S. contribution to the International Geophysical Year (IGY).

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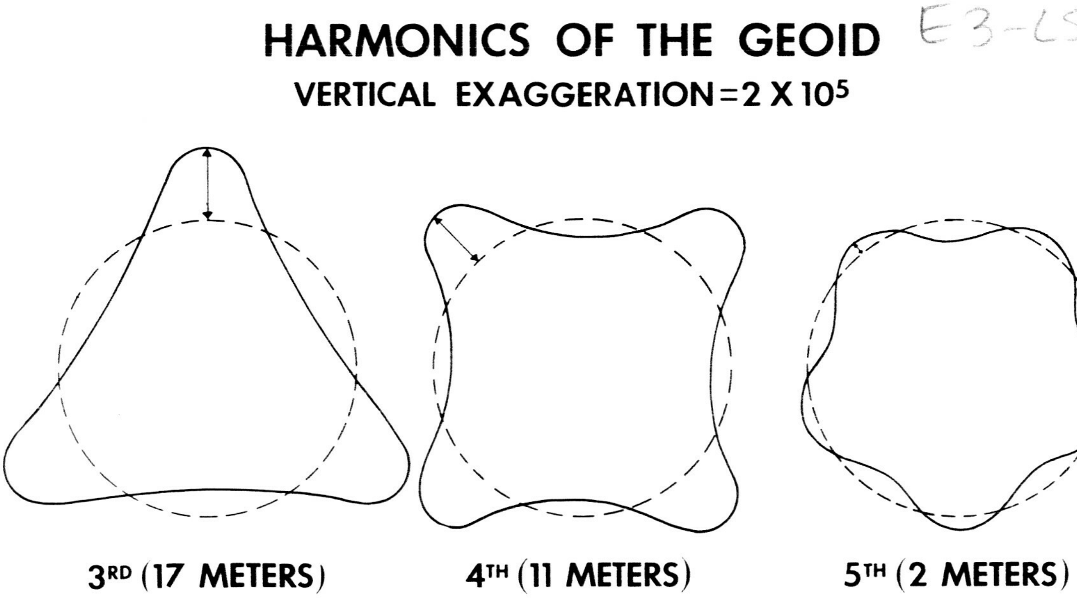


FIGURE 2. Shape of the earth: higher harmonics of the geoid.

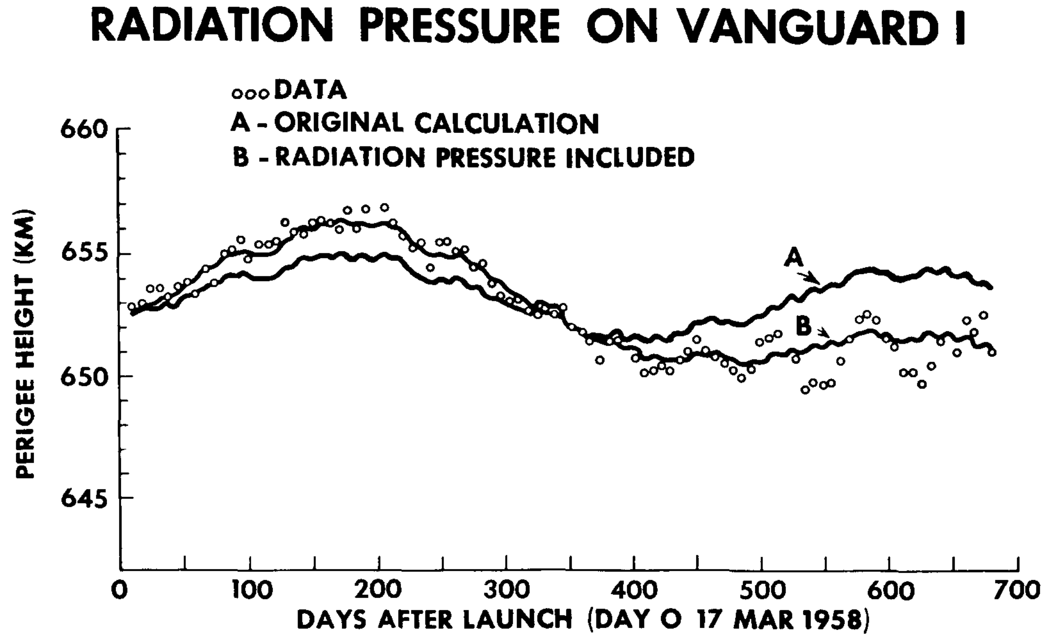


FIGURE 3. Effect of radiation pressure on the orbit of Vanguard I (O'Keefe and Bailey).

As a sidelight on the geodetic analysis of satellite orbits, the analysis of the Vanguard I orbit has been refined to such a degree that the very small effects of solar radiation pressure are clearly indicated in the orbital results. The force exerted by sunlight on Vanguard I is only 3×10^{-7} oz, and yet it has produced an observable change of 2 km per year in the perigee height of the satellite, as figure 3 shows.

Two years of tracking observations were required to reveal the effects of radiation pressure on the Vanguard I orbit, and even at the end of that time the magnitude of the pressure effect could be determined with a precision of only 30 percent. However, the Echo communications satellite has provided more accurate means for measuring the effect of these minute forces. Echo is a balloon made of thin aluminum-coated Mylar, and has a diameter of 30 meters, a weight of 70.4 kg, and an area-to-mass ratio of 10 m^2 per kg. This ratio of area to mass is 1,000 times greater than typical values for previously launched satellites, making Echo I a sensitive detector of such small effects as drag and radiation pressure. For example, the effect of radiation pressure on the Echo satellite, which still amounts only to a force of 1/50th of an ounce, is nonetheless sufficient to change the perigee height of this satellite by 500 km per year.

Atmospheric Physics

The third major area of investigation in space science concerns the control exerted by the sun over the atmosphere of the earth. It includes questions related to the circulation of the lower atmosphere, and to the structure of the atmosphere at higher altitudes.

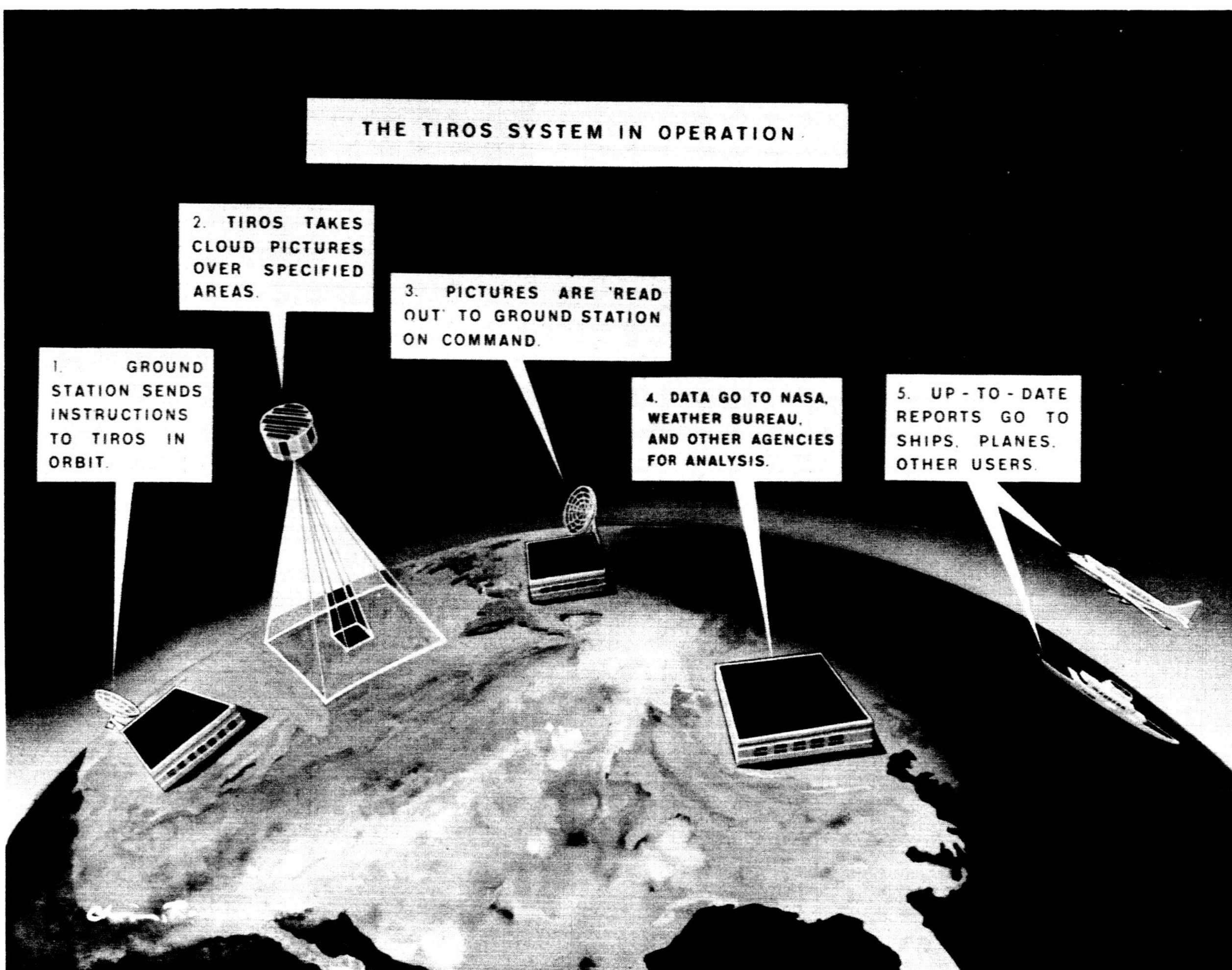
Regarding atmospheric circulation, three TIROS satellites have been launched in the past eighteen months, all carrying vidicon cameras for the global study of the cloud cover, and the latter two carrying in addition a set of infrared detectors for the measurement of the intensity of infrared radiation transmitted through the atmosphere.

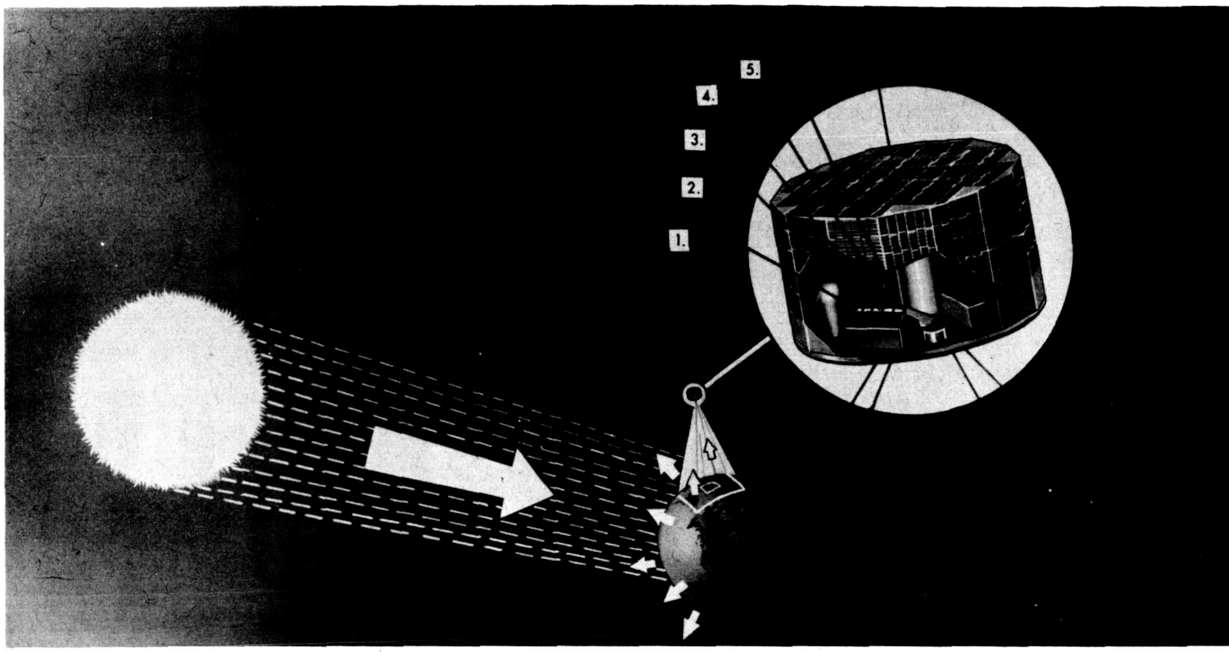
The cloud cover photographs have already yielded results of great interest when correlated with ground observations, and they have the promise of leading to a substantial improvement in weather forecasting by providing global and nearly continuous coverage of regions of weather activity. The matter of global coverage is critically important, because the success of weather forecasting has been found to increase rapidly with the size of the region covered by the observations; yet at the present time large parts of the globe are very poorly covered, and constitute regions in which weather activity can develop and grow without detection before moving out into the inhabited areas. The sparsely covered territories include the polar regions, the major deserts, and the southern oceans. Satellite coverage will greatly strengthen the hand of the meteorologist by filling in these blank portions of the global weather map, and may be expected to have important consequences for the economies of this country and the world.

The measurement of infrared radiation is less important than cloud cover photography for the immediate objectives of weather forecasting, but it should have equal or greater importance for the basic objectives of long-range forecasting and the understanding of the causes of weather. The infrared data give a direct insight into the processes of energy transfer within the atmosphere. By various processes of surface and atmospheric absorption, the energy of the incident sunlight is degraded from the visible and the ultraviolet regions of the spectrum into the infrared. A part of the infrared is re-radiated back into the space surrounding the earth, and the remainder is absorbed by the atmosphere. Local variations in this process of radiation transfer provide the sources for all weather activity.

If a good spectral distribution of infrared intensities is available, we can obtain from it the temperature distribution in the lower atmosphere, as well as the global variations in the total transfer of energy. These are vital data for the atmospheric physicist seeking the causes of weather.

TIROS—Shown in this drawing are the major orbital and ground elements of the Tiros II television-infrared weather observation system.





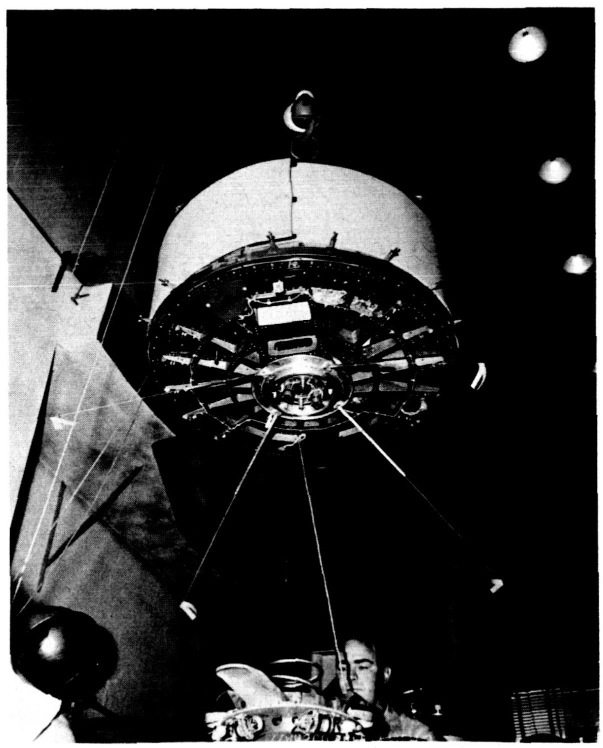
INFRARED SYSTEM IN TIROS II—Instruments in Tiros II determine the amount of radiation reflected or emitted by the earth and its atmosphere. A constant known amount of radiation strikes earth from sun (left). In Tiros, radiation is measured in different parts of visible and infrared spectrum to show: (1) Reflected sunshine; (2) total radiation of earth and atmosphere; (3) radiation direct from earth's surface or cloud tops; (4) radiation from earth's water vapor layer; (5) visible spectrum for reference.

The TIROS satellites contained broad-band infrared detectors designed only for a preliminary analysis of the infrared spectrum, and the Explorer VII satellite contained a set of radiation detectors designed for the study of the energy transfer by Verner E. Suomi of the University of Wisconsin, which although again of preliminary character, have already been quite interesting in showing the existence of large scale patterns of radiation flow that can be correlated with continental features of the weather map.

Properties of the Upper Atmosphere

We turn now to the area of research relating to the structure of the upper atmosphere and its extension into the interplanetary medium. In this area our knowledge is increasing very rapidly, and it is at present a very exciting field of research, and a very fruitful area of investigation for both the theorist and the experimentalist—one largely unexplored until now because of the paucity of data.

Parenthetically it may be noted that at the present level of activity atmospheric research will, within a few years, be a well-explored and substantial chapter of physics. Even now some grad-



TIROS II PAYLOAD—Experimental weather satellite launched from Cape Canaveral, Florida, November 23, 1960.

uate courses are being offered on the subject, and in a year or two good text books will probably appear, marking the codification and interment of the subject.

I should like first to review very briefly the state of our knowledge of the properties of the upper atmosphere, and then to mention a few recent developments of unusual interest.

Our knowledge of upper atmosphere properties—which had been limited essentially to altitudes below 100 km at the start of the IGY—has been expanded, during the IGY and during the first years of the space program, to the point where we now have a fairly good description of the atmosphere at heights up to 1,500 km, and isolated but still significant results well above that level.

We note first that density measurements have been made directly by rockets at altitudes up to about 200 km, but above that altitude direct density measurements are very difficult. However, the density may be deduced indirectly from the analysis of the atmospheric drag acting on satellites. The period of revolution of a satellite decreases steadily at a rate proportional to the drag force exerted by the atmosphere, and the coefficient of the observed rate of period change therefore gives the value of the air density suitably averaged around the orbit.

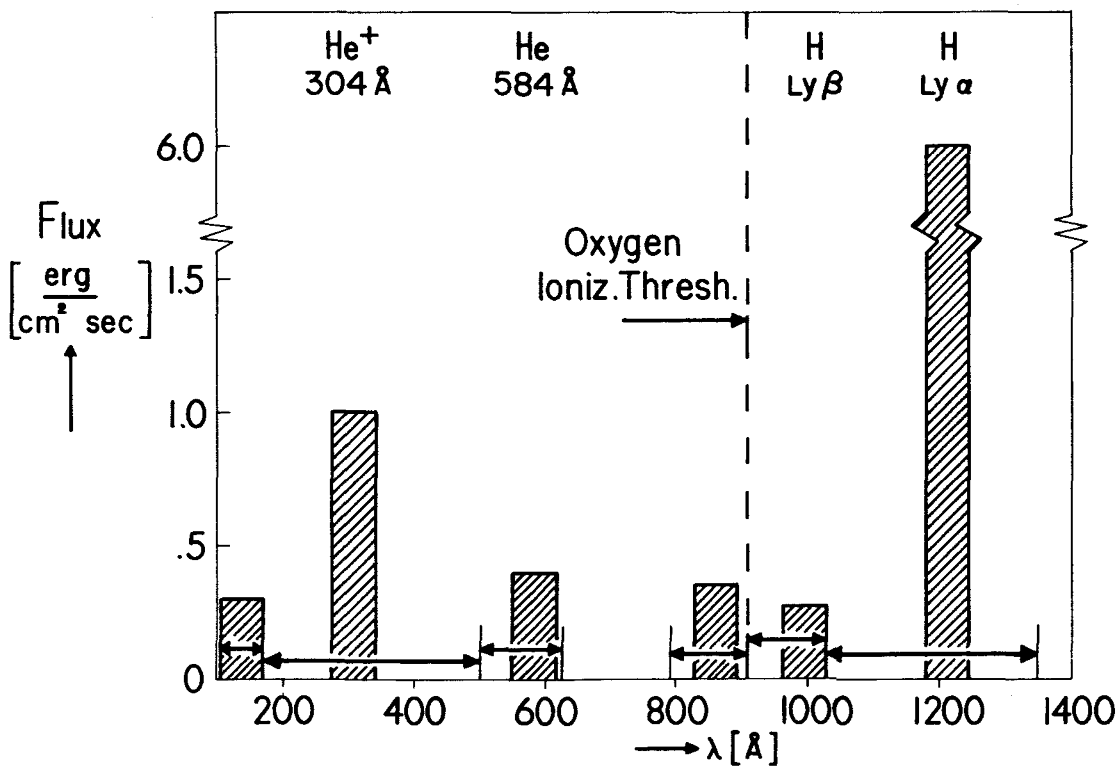
The temperature is also extremely difficult to measure directly in the upper atmosphere but on theoretical grounds it is related to the rate of change of density with altitude, according to the following formula expressing hydrostatic balance in the atmosphere,

$$d = d_0 e^{-mg(h-h_0/kT)},$$

in which d_0 and d are the density at height h_0 anu h, respectively, m is the average molecular weight per atom or molecule of air, T the temperature, g the acceleration of gravity, and k the Boltzmann constant. If the densities are known at various heights from the satellite drag data, their insertion in this formula will yield T/m. This formula is approximate but brings out the essential elements of the problem.

To find T from the density profile we must therefore know m, i.e., the composition of the air. At heights up to 1,000 km, m is known with a preci-

FIGURE 4. Spectrum of the sun in the ultraviolet (Hinteregger). S9 1-(SA-61-M/



ATMOSPHERIC COMPOSITION

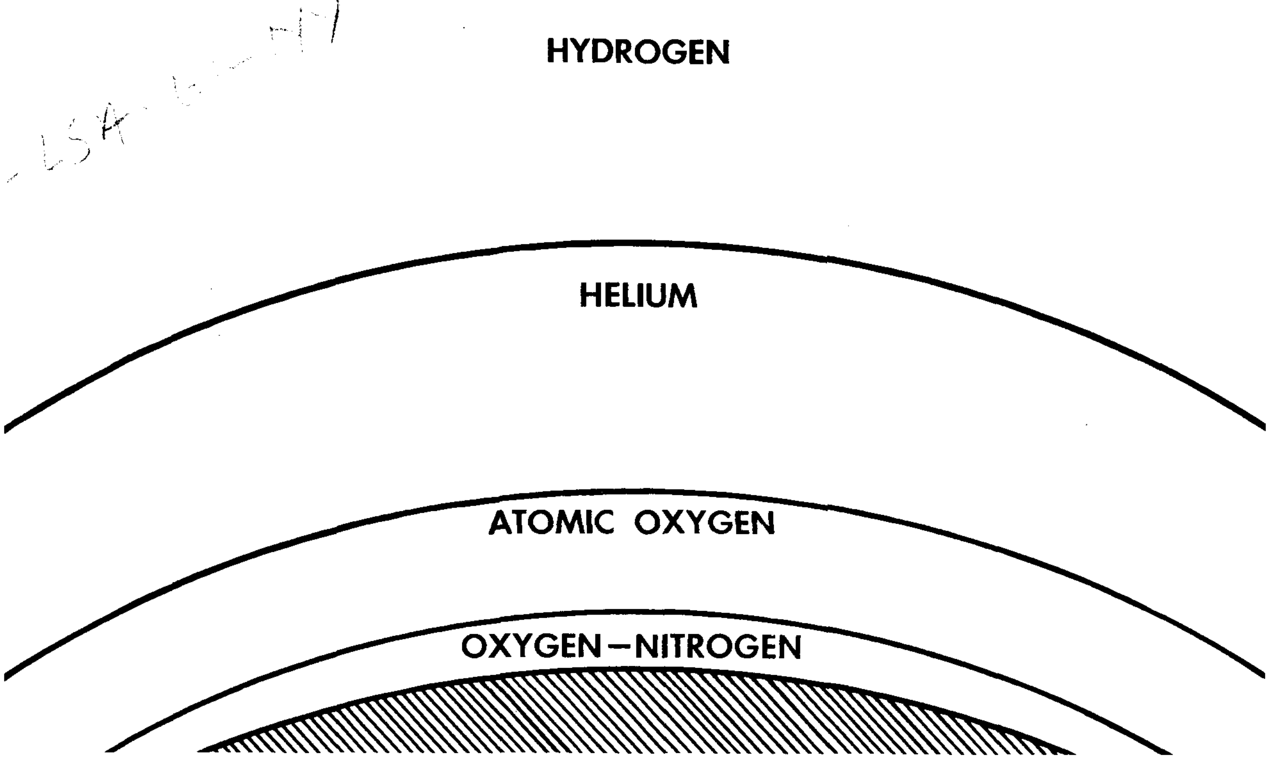


FIGURE 5. Composition of the upper atmosphere.

sion of 15 percent, by a combination of experimental and theoretical arguments, and below 1,000 km we can therefore deduce the temperature from the satellite density data within a 15 percent limit of error.

Above 1,000 km the uncertainty in the composition becomes large and troublesome. The difficulty is that at the lower altitude we know the air to be composed of oxygen and nitrogen, and can calculate the proportions of these two gases rather well, but at the highest altitudes these gases have settled out of the air, because they are relatively heavy and are concentrated near the surface of the earth by the force of gravity. The lighter gases, which are present only in trace amounts in the lower atmosphere, are not as tightly bound to the surface of the planet by gravity, and they therefore dominate the composition of the air at sufficiently high altitudes. Of these gases hydrogen is the lightest, and for this reason it was believed to be the dominant constituent of the air above the oxygen-nitrogen layer. The emergence of the hydrogen atmosphere was thought to come at an altitude of about 1,200 km. However, a few months ago Marcel Nicolet, National Space Research Center, Brussels, Belgium, suggested, on the basis of an initial examination of the density data, that between the oxygen-nitrogen atmosphere and the hydrogen atmosphere there should lie a layer of helium. Shortly after Nicolet's suggestion, experimental evidence for an intervening helium layer was obtained independently by Robert E. Bourdeau, E. C. Whipple, Paul C. Donnelly, and S. J. Bauer of Goddard Space Flight Center, working from Explorer VIII ion trap data, and by W. B. Hanson of the Lockheed Missiles and Space Co. in Palo Alto, working with ion density data obtained by L. C. Hale.

Figures 5 and 6 present a summary of the major properties of the atmosphere, revised in accordance with these recent developments. They show a mixture of nitrogen and oxygen molecules up to about 120 km, a layer consisting predominantly of atomic oxygen between that height and 1,000 km, a layer of helium from 1,000 to 2,500 km, and a hydrogen atmosphere extending out into the interplanetary medium above 2,500 km.

The slope of the density curve (A) in figure 6 corresponds to a temperature of 1,350 degrees, which is a good average value for the temperature of the upper atmosphere. It has been derived partly from the satellite measurements of density at high altitudes and partly from a variety of independent measurements of the electron density profile, obtained from sounding rocket and satellite experiments. All of these agree within a spread of about 200°.

Also shown in the figure are two curves B and C, which represent the diurnal variation, i.e., the density of the air at different times of day, namely around 4:00 p.m. and 4:00 a.m., respectively. From the slopes of these curves we obtain a temperature of 1,650° for the afternoon atmosphere, and a temperature of 1,050° for the night atmosphere.

Marcel Nicolet

Robert Bourdeau

W. B. Hanson

E. C. Whipple, Jr.

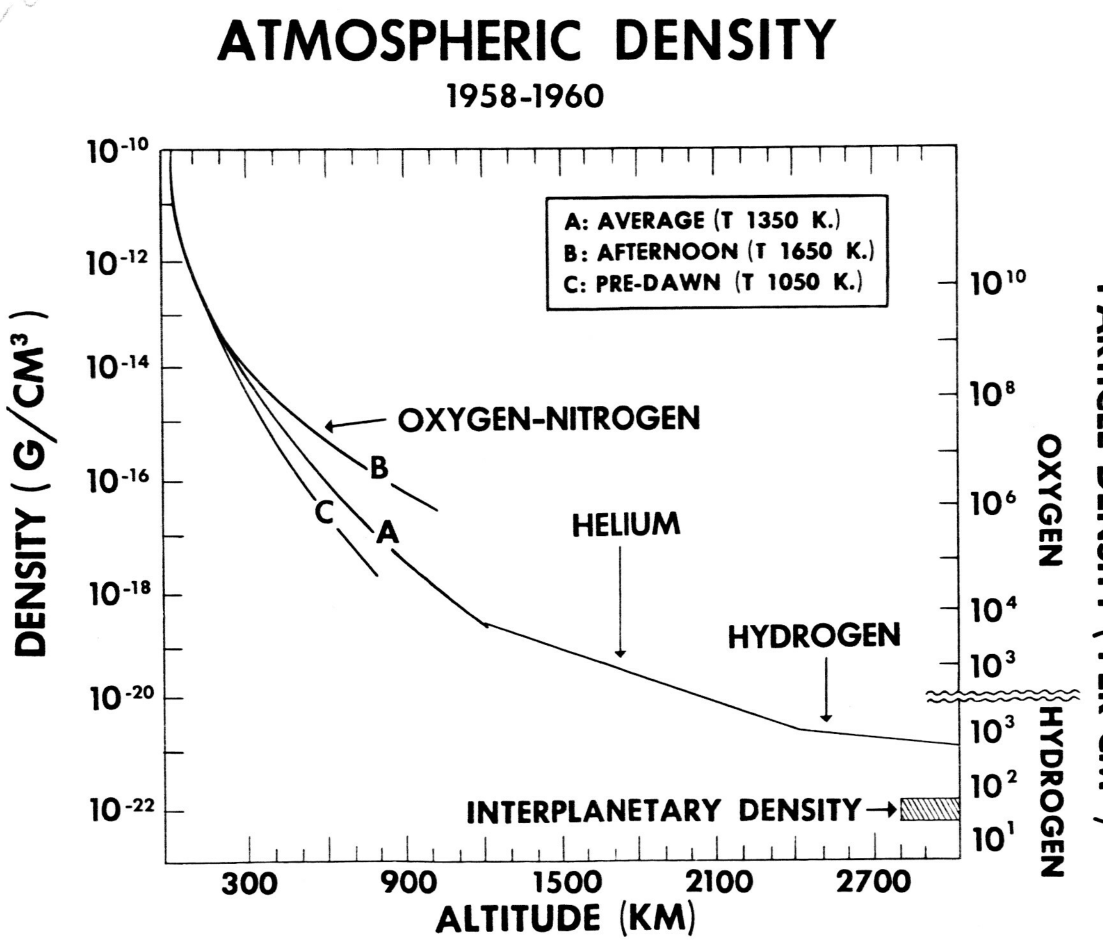


FIGURE 6. Density of the upper atmosphere (Kyle and Jastrow).

This diurnal variation of temperature was uncovered in the course of the analysis of satellite drag data, principally by W. Priester, Goddard Space Flight Center, L. G. Jacchia, Harvard University Observatory, and D. G. King-Hele, Royal Aircraft Establishment, Farnborough, Hants, England. The satellite data are quite good for detecting such effects, because the drag is concentrated at perigee, the part of the orbit where the density is greatest. As the plane of the orbit rotates in space the perigee point moves from the dark to the sunlit side of the earth and back again, and the drag data trace out the diurnal dependence of atmospheric properties. Figure 7 shows the results of a full analysis of the diurnal variation in satellite drag, carried out by Priester, partly at the Bonn Observatory in Germany and partly in his current position with our research group in New York City. The Priester curve may be compared with several determinations of electron temperature at different times of day, also shown in figure 7, which were obtained by physicists at Goddard and at Lockheed from the Explorer VIII ionosphere satellite and from several sounding rocket flights. All data in figure 7 have been reduced to the mean level of solar activity in November 1960, which was the period of the Explorer VIII measurements.

W. Priester

D. G. King-Hele

The detailed study of satellite drag has in fact been a very valuable source of information on atmospheric properties. Jacchia of the Smithsonian Astrophysical Observatory did the first careful spadework in what seemed to many at the

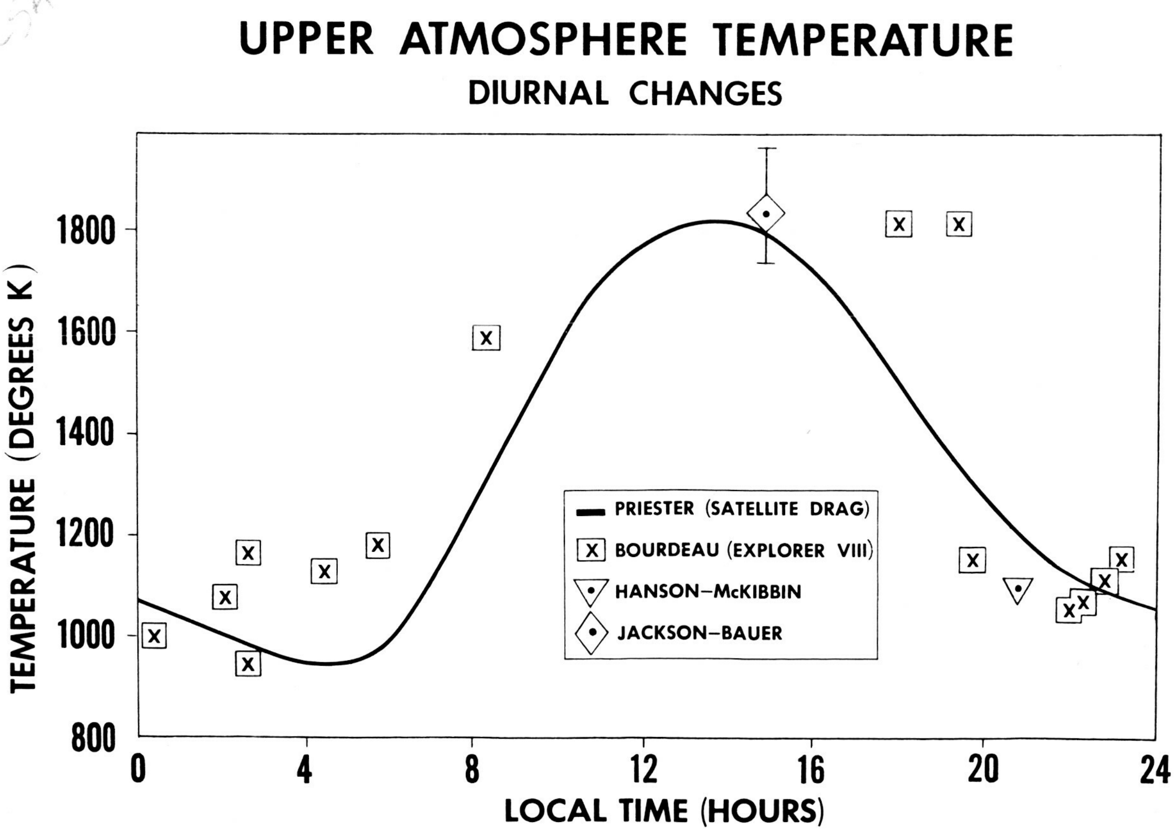


FIGURE 7. Diurnal variations in the temperature of the upper atmosphere, reduced to average solar activity of November 1960 (Priester).

time to be a very unpromising garden. The most interesting result of his investigations was the discovery that the upper atmosphere is extremely responsive to solar control, undergoing excursions in density which were lately found to be as much as a factor of 100, and in temperature by hundreds of degrees, according to the level of solar activity. These variations first came to light in Jacchia's analysis of the orbit of Sputnik II, in the winter of 1957–58, during the course of which he discovered that from day to day there were large and apparently random fluctuations in the drag acting on that satellite. Jacchia discerned a slight but significant tendency towards a 27-day period in these fluctuations which matched the period of rotation of the sun, and concluded that their cause might be variable solar radiation. His report came to the attention of Priester in Germany, who thought that these variations might be produced by radiation emitted from the vicinity of sunspots; and to test his idea he placed Jacchia's Sputnik II drag curve against a graph of data showing the day-to-day variations in the intensity of the radio waves emitted by the sun at wave-

William Kaula

Luigi G. Jacchia

lengths of 20 cm. The intensity of these waves is an excellent indicator of the frequency of sunspots and the general level of solar activity. Priester found agreement in all variations of both graphs. On hearing of Priester's result, Jacchia placed his drag curves against a plot of the 10 cm solar radio emission, which is also a good measure of solar surface activity, and also found a close correlation. Jacchia's curves are shown in figure 8. They show also that the same variations appear in both Sputnik III and Vanguard I, proving that they are a feature of the atmosphere rather than a peculiarity of one satellite.

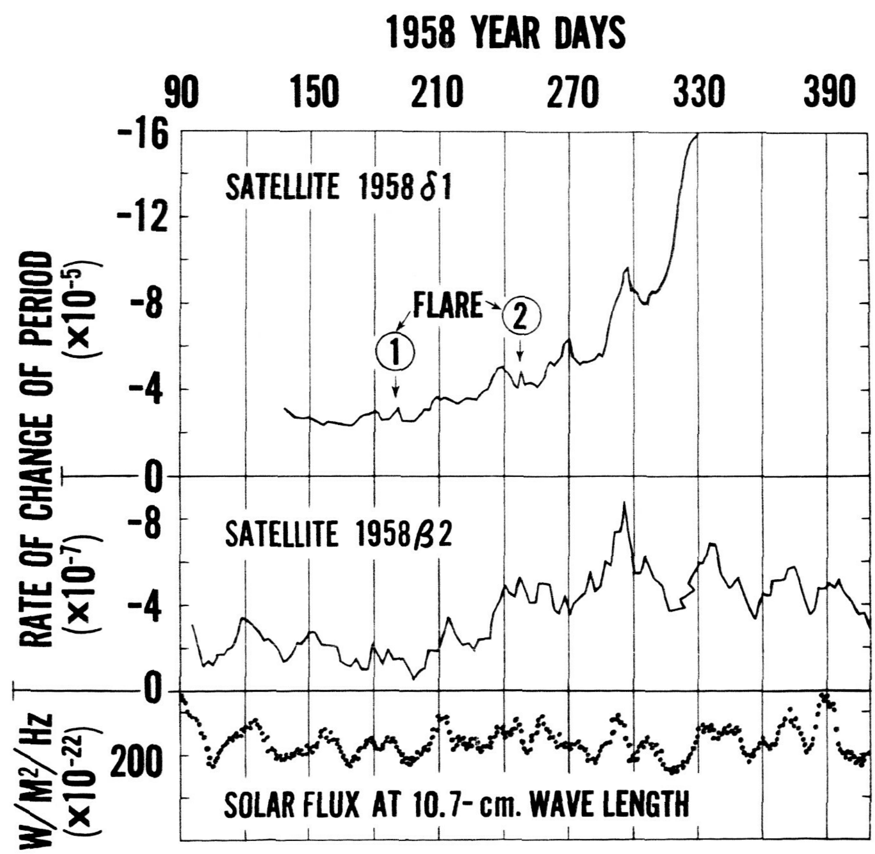


FIGURE 8.—Correlation of satellite drag variations with solar activity (Jacchia).

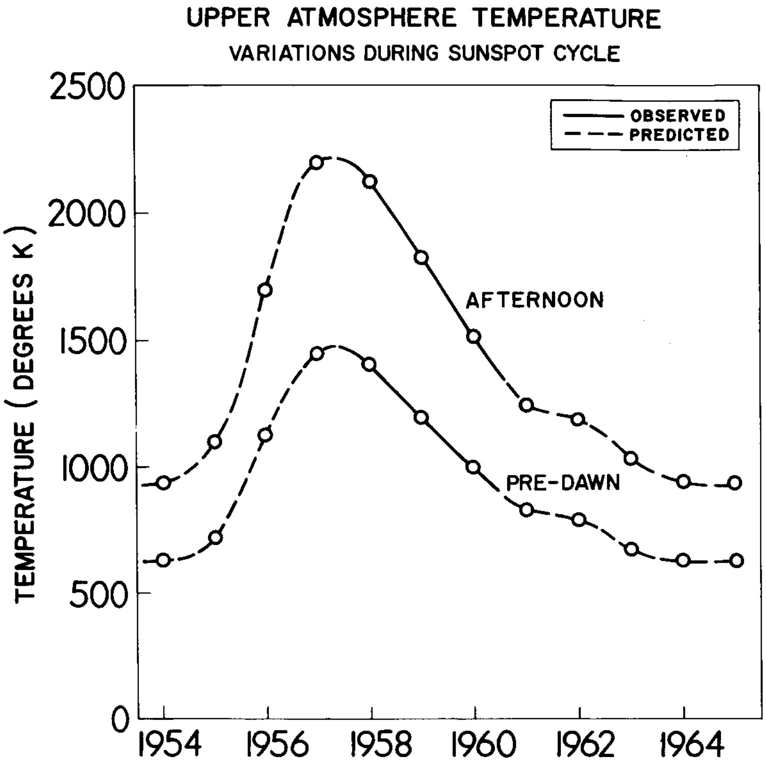


FIGURE 9.—Variations of upper atmosphere temperature during the sunspot cycle (Priester).

The significance of this agreement can be understood as follows: During the maximum of the sunspot cycle—and 1958 was the year of the maximum in the last cycle—the surface of the sun is the scene of great activity, marked by sunspots, and by hot condensations well above the sunspots in the solar corona with temperatures of some millions of degrees. These regions are known to emit a radio flux in the 3 to 30 cm range and are supposed to emit energetic radiation in the extreme ultra-violet and X-ray band. We have further reasons to believe that the flux in the extreme ultraviolet is correlated to the radio flux. When an active region faces towards the earth in the course of the sun's rotation, extreme ultraviolet radiation emitted from these active regions is absorbed in the upper atmosphere, primarily at altitudes between 150 and 250 km. The precise correlation between solar activity and density, found principally by Jacchia, Wyatt, and Priester, suggests that the amount of energy transferred to the earth is sufficient to heat the atmosphere appreciably, causing an upward expansion and a large increase in the density of the exceedingly thin air at high altitudes. This discovery provided the first direct evidence regarding the effects of solar surface activity on fundamental atmospheric properties.

The continuing analysis of the correlation has given us a rather full picture of the degree of solar control over the upper atmosphere. The study has now been carried on over a sufficient number of years so that it has been possible to detect the variation in the yearly average of these effects as we move from the maximum to the minimum of sunspot activity. Figure 9 represents results obtained by Priester on the change of upper atmosphere temperature between the start of satellite observations at the end of 1957 and the latest analyses available for the past year. After 3 years of analysis, Priester has a very accurate idea of the correlations between the 20-cm radiation and upper atmosphere temperatures, and he also knows the variations in the 20-cm radiation which can be expected during this sunspot cycle on the basis of solar observations in previous years. In this way he has been able to predict the temperature of the atmosphere during the coming years of the sunspot minimum, within the limitations of our uncertain knowledge of the molecular weight at great altitudes. The results are shown in figure 9, which contains separate curves for the afternoon and predawn atmospheres. According to these curves we can expect the predawn temperature of the atmosphere to reach a low point of 500° K in 1964.

The Magnetosphere

The density of the upper air merges into the density of the interplanetary gas at an altitude of about 1,000 km, and this level should mark the boundary of the atmosphere. However, early in 1958 Van Allen discovered, by the analysis of geiger counter data from Explorer I, that there was an additional layer of particles in the upper atmosphere, which were eventually found to reach out to about 100,000 km.

Since the first discovery there have been a large number of investigations of these particles by sounding rockets and satellites, the most recent and most extensive experiments in this country being those carried out by Explorer XII, while in the USSR important experiments have been carried out by Sputnik III and the three Luniks.

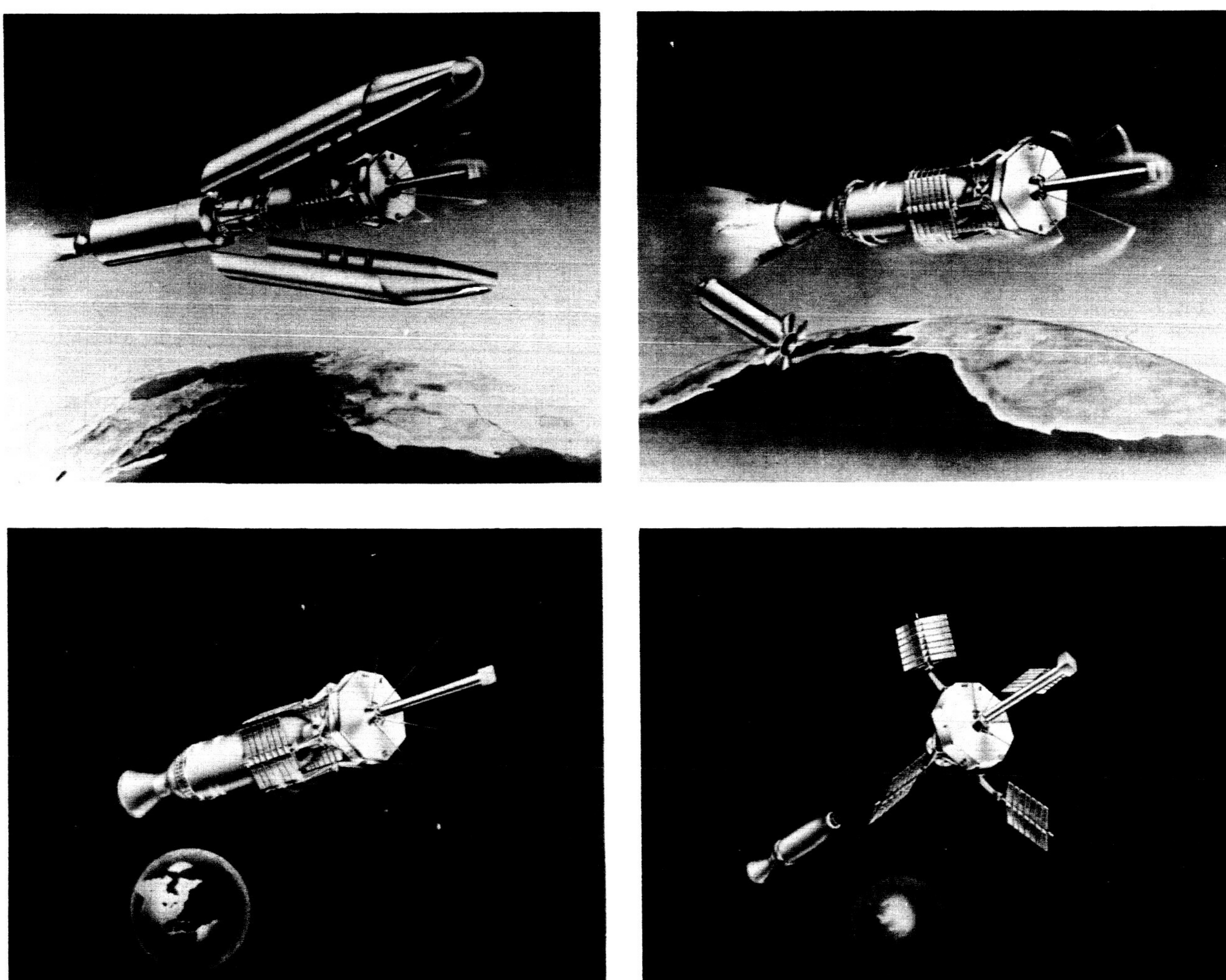
EXPLORER XII

Upper left: The Delta is more than 40 miles high and 90 miles downrange when the second stage fires. Forty seconds later explosive bolts tear away the fairings which enclose the S–3 satellite.

Upper right: After coasting to about 1,300 miles downrange and reaching an altitude of 160 miles, explosive bolts and retro rockets separate the second stage, and the third stage is spun up and fired.

Lower left: Yo-yo weights despin the third stage and S–3 satellite, and exhaust gases dissipate, during a 24-minute coast after third stage burnout, which occurs almost 2,000 miles from Cape Canaveral when the engine and S–3 are traveling at a velocity of more than 24,000 miles per hour.

Lower right: The four solar paddles with solar cells for converting sunlight into electrical energy are released when an explosive-actuated cutter severs a nylon lanyard after the coast period. The Delta's third stage is separated from the S–3 by explosive bolts and a spring mechanism.



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James A. Van Allen

The data show that these particles have a rather low concentration; nonetheless they are bound to the earth and move with it through space, hence must be considered as a part of the atmosphere. They consist of charged particles with energies as high as millions of volts, which are produced in various ways at high altitudes and are trapped near the earth for extended periods of time by the geomagnetic field.

This additional layer of particles is called the magnetosphere, because it exists only by virtue of the presence of the earth's magnetic field. The discovery of the magnetosphere by Van Allen was the most significant scientific discovery of the IGY and of the first years of the space program. It has generated a great volume of research and has thrown a new light on the problem of solar-terrestrial relationships.

Interest in the Van Allen particles was initially concentrated on the radiation hazard which they might present to manned space travel, but the scientific importance of this discovery is related less to that problem than to the geophysical role of the Van Allen particles in influencing the properties of the upper atmosphere. It appears that the Van Allen zones are related to the process by which energy is transferred from the sun to the earth in the form of particles, magnetic fields, and radiation, at the time of major solar flares. The effects of this energy transfer involve not only the gross changes in upper atmosphere properties which we have mentioned, but also a variety of other effects of great geophysical and practical interest. These include magnetic storms, the aurora, radio communication disturbances; and there has even been some suggestion of a correlation between flare activity and the weather. Now it has been found that flares also produce enormous changes in the intensity of the Van Allen belts, which are connected in some way not yet clearly understood to the other geophysical effects accompanying solar activity. The available evidence suggests that these Van Allen zones, and the whole magnetosphere of which they are a part, constitute a reservoir in which solar flare energy can be stored in the form of trapped particles for a considerable time, until some subsequent solar event disturbs the magnetic field and dislodges particles from the Van Allen belts as apples are shaken from a tree. As to the mechanism of the shaking, it is believed that when the incident solar plasma cloud impinges on the geomagnetic field, it produces perturbations in the field which scatter the particles out of their spiralling orbits around the lines of force. When the particles are dislodged from the magnetosphere they descend through the horns of the Van Allen zone, transferring their kinetic energy to the atmosphere by ionizing collisions. This is probably the cause of the aurora.

The particles of the highest energy have the largest Larmor radii of gyration and move in the most sweeping spirals. These are the least firmly trapped and therefore the most easily dislodged. The less energetic particles are wound very tightly around the magnetic field lines, and are not as easily dislodged. Furthermore, the outermost region of the magnetic field is the weakest part of the field and therefore the region most seriously disturbed by the incident plasma cloud. Thus, putting these two points together, we conclude that the most energetic Van Allen particles will be found primarily at the closer distances to the earth, while the outermost regions will contain few of these, and consist primarily of the slower and less energetic particles. Moreover, since the outermost portions of the trapped particle zone are the portions which are connected through magnetic lines of force with the zones of auroral activity, we expect that it must be the softer Van Allen particles which are principally responsible for auroral disturbances.

These qualitative remarks lead us to suggest that in future studies of the geophysical effects of the Van Allen zones the emphasis should be placed on the low energy components of the trapped particle spectrum. These are particles which would have escaped detection in satellites flown up to now, because they are below the thresholds of the detectors included in those first-generation experiments.

Some suggestions of the geophysical importance of this hidden population of soft particles appeared in the records of the theoretical conference on the geophysical effects of the trapped particles, which the Goddard Center organized a year ago last September; and more recently some definite experimental facts have begun to emerge regarding the existence of soft trapped particles, and their geophysical significance. In the USSR, K. I. Gringauz, Radio Engineering Institute, Academy of Sciences, USSR, and his collaborators have published the results of data from ion traps flown on Luniks II and III, which indicate large numbers of electrons with energies as low as 200 volts. The measured fluxes are of the order of 10^8/cm^2 sec. Gringauz and Sergy M. Ritov, P. N. Lebedev, Physics Institute, Academy of Sciences, USSR, have further calculated the drift current associated with these low-energy trapped electrons, and have shown that this current could account for the perturbations of the earth's magnetic field measured on Explorer VI by C. P. Sonett, NASA Headquarters, Paul J. Coleman, Jr., NASA Headquarters, and their collaborators. Also very recently Hans E. Hinteregger, Air Force Research Division, Bedford, Massachusetts, reported in a private communication, based on preliminary results of a satellite experiment, that at an altitude of 3,500 km he found a heavy concentration of electrons with energies between 10 and 20 volts. The fluxes of these ranged from 10^8 to 10^{10}/cm^2 sec. Calculations which I made with D. D. Cattani, Goddard Space Flight Center, indicate that these fluxes, at the indicated energy, are to be expected as a trapped population of photo-electrons produced by solar ultraviolet radiation, with wavelengths in the neighborhood of 300 Angstroms, if we take for our calculations the ultraviolet intensities measured by Hinteregger in his rocket experiments.

The instruments on board Explorer XII go to lower energies than those on previous energetic particle satellites, and the data now in process of analysis could make an important contribution to the resolution of the points which have been raised regarding the importance of the very low-energy particles in the Van Allen zones.

The Interplanetary Medium

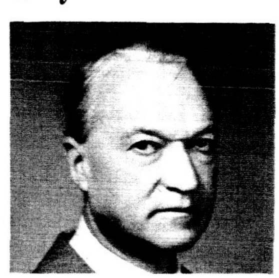
From the magnetosphere, we are led finally to the properties of the surrounding interplanetary medium, and to a consideration of the manner by which solar disturbances are propagated through this medium to the earth. This is the area which has been the scene of the most rapid advances and most interesting developments during the past year.

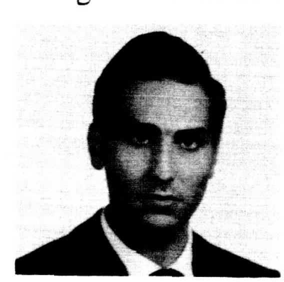
The properties of the quiescent interplanetary medium have been studied with instruments carried on board the Luniks, Pioneer V and Explorer X. The Explorer X experiments were especially valuable in this connection because they included both a magnetometer, developed by Heppner and his collaborators at the Goddard Center, and a low-energy particle detector, developed by Bruno Rossi and Herbert Bridge, Massachusetts Institute of Technology, and their collaborators at MIT, and designed specifically for the study of the interplanetary plasma fluxes. Because of the high electric conductivity of a plasma, the motions of the interplanetary plasma and the configurations of the magnetic field are closely associated, and a measurement of both features gives us a doubly powerful mode of attack on the properties of the medium.

The analysis of the Explorer X data is still in progress, and only preliminary results can be given. The magnetometer readings indicate that at geocentric distances ranging from two to six earth's radii the magnetic field departs substantially from the computed dipole field, the departures having negative signs and a magnitude of approximately 100 gammas. These results are consistent with magnetic field measurements made in previous space flights. Between 10 and 20 earth's radii, the magnetometer indicated a superposition of the dipole field on a steady field having a magnitude of 10 or 20 gammas, and directed away from the sun at a stream angle of 30° or 40°.

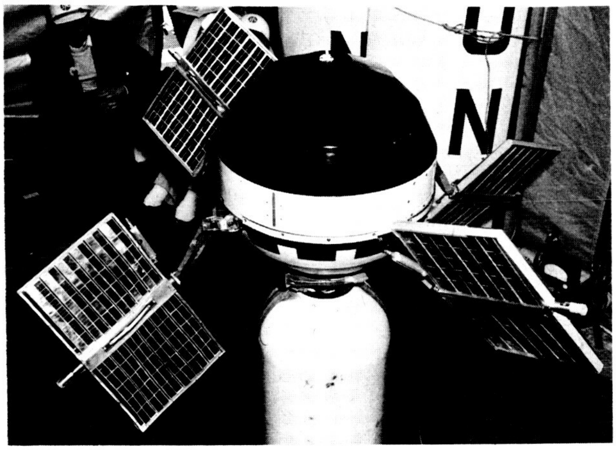

Charles Philip Sonett


James Heppner


Bruno B. Rossi


D. D. Cattani

Beyond 20 earth's radii, the field was less regular, occasionally displaying large fluctuations in magnitude and direction. In the same region, above 20 earth's radii, the plasma probe on Explorer X indicated fluxes of positive particles ranging up to $10^9/cm^2/sec$, with a minimum energy of 500 volts. These fluxes were strongly correlated with the magnetic field, in such a way that the presence of plasma usually coincided with a weak and fluctuating field; whereas when the plasma was absent, the field was usually strong and directed away from the sun.



PIONEER V—Space Probe on top of third stage Thor-Able. The rocket forming third stage appears as a cylindrical tank coming up through an opening in the platform near the top of the launching gantry, and bolted to the bottom of the spacecraft.

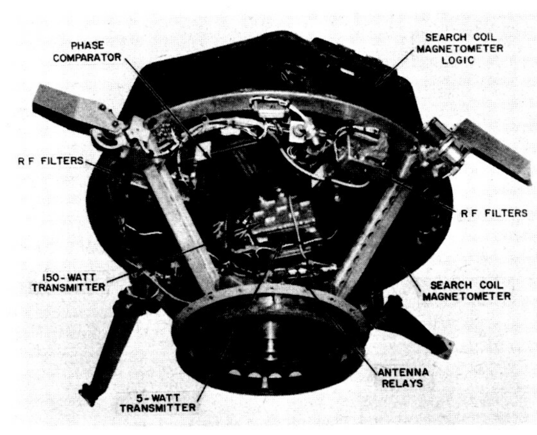
Propagation of Solar Plasma Clouds

Turning next to the nature of the medium when filled with solar particles, our understanding of the manner of propagation of solar disturbances has been greatly advanced during the past year, and it can now be said that we have an accurate conception of the complicated and originally rather mysterious sequence of events which accompany the phenomenon of solar activity. The ideas which we will discuss in this connection principally reflect the work of Thomas Gold, Cornell University, Kenneth McCracken, Massachusetts Institute of Technology, and J. A. Simpson, University of Chicago, although several other investigators have also made important contributions to the subject.

The rapid progress during this recent period has resulted in part from a fortuitous circumstance, in which on several occasions a succession of major flares occurred at intervals of a day or so, and on an element of the sun's surface located in such a position that their products could reach the earth. One of these multiple events, the most energetic to be observed in nearly five years, occurred in the period November 10–19, 1960. Another important multiple event, occurring in the period March 30–April 1, 1960, provided an especially fortunate occasion because at that time there were in space, in operating condition, an interplanetary probe (Pioneer V), a near-earth satellite (Explorer VII), and at the same time on the ground a network of observing stations—all equipped to measure particle fluxes or magnetic field strengths, and therefore providing a three-pronged attack on the problem.

The occurrence of such a succession of flares is valuable for the study of interplanetary conditions because when the cloud from the first flare has filled the space between the sun and the earth, the particles emitted in the subsequent flares must traverse this cloud en route to us; and by observing the circumstances of their transit over our instruments in space, and their arrival in the atmosphere, we can judge the forces which act on them during the flight, and thus deduce some information regarding the magnetic field and other properties of the intervening medium.

A very interesting picture has developed out of the analysis of these multiple flare events. We will discuss the general circumstances of the phenomenon first, and then describe the data on which the theoretical description is based.



PIONEER V—Without its aluminum shell, the 94.8 pound planetoid probe looks like this from the bottom. The planetoid was launched March 11, 1960, from Cape Canaveral by the National Aeronuatics and Space Administration.

We first note that when a flare occurs, it produces a burst of radiation and particles of various energies. If the flare erupts in the direction facing the earth, the radiation and the clouds of charged particles travel across space to collide with our atmosphere. The radiation travels at 186,000 miles per second and reaches the earth in 8 minutes, but the particle clouds typically expand at the much slower rate of 1,000 miles per second, at which speed they reach the neighborhood of the earth after about 24 hours. The energy carried by these solar streams is less than one millionth of the energy radiated by the sun in the form of visible light; but they appear to be responsible, nonetheless, for the variety of effects already mentioned in the discussion of the magnetosphere. We connect the flares with these phenomena, and assume that there has been an outpouring of flare energy to produce them, because this whole pattern of event invariably occurs about 24 hours after a major flare is observed.

We note also that solar flares occur in regions close to sunspots which have intense magnetic fields (as much as 1,000 gauss). They are connected in some way with the generation of the flares. As the flare develops, and the cloud of charged particles erupts from its site and spreads out into interplanetary space, it drags with it the magnetic field of the flare site, which is frozen in the plasma cloud and must move with it because of a high electrical conductivity of the plasma. Thus the expanding cloud draws out the lines of magnetic force like loops of taffy.

The strength of the magnetic field diminishes as the cloud expands, but even at the distance of the earth's orbit the field within such a cloud will still be 10^{-4} to 10^{-3} gauss, or some 10 to 100 times greater than the field within the quiescent interplanetary medium.

A magnetic field of this strength extended over an appreciable fraction between the sun and the earth presents a formidable barrier to the passage

J. A. Simpson

Kenneth G. McCracken

Thomas Gold

Scott E. Forbush

of charged particles. Such clouds entering the cloud from outside will be turned back in a distance of the order of the Larmor radius for a particle moving in the field within the cloud; and if, for particles of a given energy, the Larmor radius is substantially smaller than the smallest dimension of the cloud, then particles of that energy cannot penetrate the cloud boundary. For example, for a proton with an energy of 1 mev or a velocity of 10^{9} cm/sec, moving in a field of 10^{-4} gauss, the Larmor radius is 10^{9} cm, which is very small in comparison to the sun-earth distance of 10^{13} cm. Such a particle cannot penetrate the boundary of the solar plasma cloud.

Even a typical cosmic ray particle with an energy of 1 billion volts will have a Larmor radius of $\approx 10^{11}$ cm, and will be turned away. Of course the most energetic cosmic rays will be able to penetrate; so that the fraction which can penetrate will depend on the strength of the field.

Thus we expect that a cosmic ray detector on the earth will show a decrease in counting rate as the cloud sweeps over our planet, the magnitude of the decrease depending on the extent of the cloud and strength of the magnetic field within it.

Some 20 years ago it was discovered that such a decrease of cosmic ray intensity does in fact frequently occur about one day after a solar flare. The discovery was made by Scott E. Forbush, Carnegie Institution, Washington, D.C., and the effect is commonly called the Forbush decrease. Until a few years ago we were not certain of the cause of the Forbush decrease; we did not know whether it originated in conditions centered on the sun and extending into the interplanetary medium, or was centered on the earth and associated with disturbances in the geomagnetic field.

These two hypotheses—the heliocentric and the geocentric—were debated in the symposium on space exploration held in Washington, D.C., in April 1959, and an experiment was proposed for the resolution of the question, involving the simul-

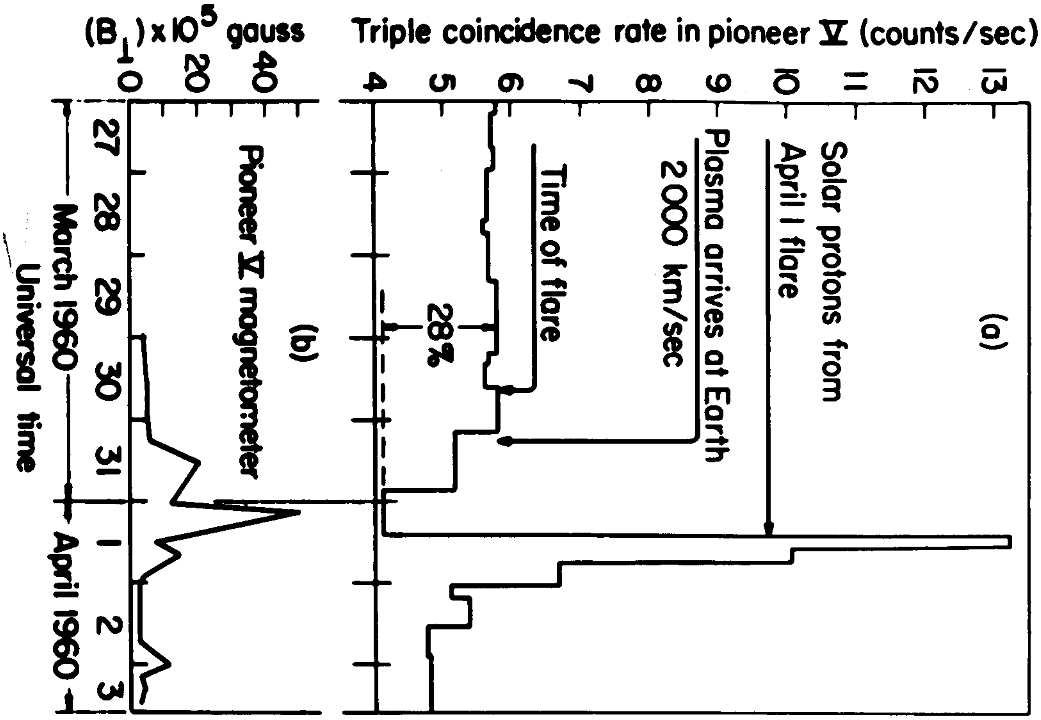


FIGURE 10. Comparison of particle and magnetometer data from Pioneer V (Simpson, Fan, and Myer; Sonett, Coleman, and Davis).

taneous search for Forbush decreases in space and on the earth. This experiment was carried out a year later by Pioneer V, during the solar event of April 1960.

The Pioneer V data, which were obtained by Simpson et al., from the University of Chicago, showed that a Forbush decrease occurred at the position of the probe, out in interplanetary space 3 million miles from the earth, at about the same time that it was observed here on the ground. This observation proved that the decrease was heliocentric and connected with the passage of a solar distrubance through the interplanetary medium, rather than geocentric and connected with the earth's magnetic field. At the same time, the magnetometer which had been placed on board Pioneer V by Sonett et al. from the Space Technology Laboratory showed a marked increase in the strength of the interplanetary magnetic field as the plasma cloud swept over the craft and the local Forbush decrease set in. At that juncture the interplanetary field strength increased about tenfold over its previous quiescent value of 2×10^{-5} gauss, and it maintained this high value for 2 days (fig. 10).

If we accept this picture of the combined propagation of solar plasma clouds and magnetic fields, we must expect an additional phenomenon, which need not occur in every flare but must occur at least occasionally, and whose detection would provide strong support for these ideas. The effect in question is the converse of the Forbush decrease, namely, an increase in the intensity of *solar* cosmic rays, occurring simultaneously with the decrease in the general cosmic ray intensity. That is, the same magnetic fields which keep externally produced cosmic rays away from the plasma cloud must keep other energetic particles trapped inside the cloud, provided we have arranged to have these particles placed within the cloud in some way initially, as by injection into the cloud from the sun itself.

In other words, the fields within the cloud give it the properties of a magnetic bottle, and if the walls of the bottle are strong enough to turn away charged particles from outside, they must also be able to retain charged particles which are already inside.

The means for placing energetic charged particles within the cloud can only be injection into the mouth of the bottle at the site of the flare. We already know that these flares frequently generate streams of energetic protons with energies near 100 mev, and very occasionally produce particles of still higher energies in the true cosmic ray range of a Bev or more. These solar cosmic ray protons could be produced in the same flare which ejected the plasma cloud, or they could appear in a subsequent flare which developed at the same spot on the sun's surface, and therefore was inside the mouth of the magnetic bottle. Whenever these circumstances occur, detection at the earth will register a sharp increase in the arrival of 100 mev protons, provided the earth is also inside the magnetic bottle associated with the initial flare, at the time of the solar proton outburst. However, if the earth is outside the bottle there will be no increase, or at most a moderate increase associated with the slow leakage of energetic protons through the walls of the bottle.

With these remarks in mind, we turn to the examination of the data for the solar events of March and November 1960. We start with the event of March 1960, which has been discussed by Simpson, Sonett, and others.

Both the Pioneer V space probe and the Explorer VII satellite were out in space at the time and equipped with instruments specifically designed to detect the effects of such a great solar event. At that time Pioneer V was three million miles from the earth and roughly in a line with the earth and sun, while Explorer VII was orbiting the earth at an altitude of 800 miles above the surface.

On March 30, 1960, at 1455 GMT a large flare of Class 2+ occurred, which lasted until 1858 GMT on that date. At around 1200 GMT on March 31, or about 22 hours later, a magnetic storm began, accompanied by a Forbush decrease of cosmic ray intensity. The same Forbush decrease registered on the counters in Pioneer V, as already noted (figure 10). The 22-hour interval between the flare and the commencement of the magnetic storm indicates that the particles of the plasma cloud took about that amount of time to travel from the sun to the earth, and therefore were moving at a speed of about 1,200 miles per second.

At 0845 GMT on April 1, a second major flare of Class 3 began and lasted until 1222 GMT. When this second flare started, the plasma cloud emitted during the first flare had already enveloped the earth. The second flare, unlike the first one, emitted a burst of very fast particles, protons with energies of the order of 100 mev, in addition to the usual cloud of plasma.

The earth and the Pioneer V spacecraft had already registered Forbush decreases from the first flare, indicating that these two objects had been enveloped by the initial plasma cloud and therefore were inside the magnetic bottle at the time of emission of the burst of fast protons. Thus there should have been a prompt response to the fast proton emission from the instruments in Pioneer V. These particles were in fact detected directly, as they passed Pioneer V shortly after the second flare, by counters placed on-board by Simpson and his collaborators at the University of Chicago. The detection of the fast protons by Pioneer V appears very clearly in the upper curve of figure 10 as a sharp increase on April 1, temporarily erasing the previous Forbush decrease.

Thus the fast particles ejected by the second flare had to travel through the previously emitted cloud of plasma all the way from the sun to the earth. They arrived here at 0945 GMT. Their precise time of arrival at the earth is fixed by the report of Harold Leinbach, of the University of Alaska, indicating that at this time there began a strong absorption of radio waves in the polar atmosphere, an effect which is commonly produced by such a burst of solar protons. The flare had started at 0845—an hour before the onset of polar cap absorption; therefore the transit time for these particles was about one hour. If the 100 mev protons had traveled directly from the sun to the earth, they would have required 18 minutes for the trip.

Thus the magnetic fields in the plasma cloud produced by the first flare lengthened the transit time for the fast protons by approximately a factor of 3. From this result two conclusions may be drawn: First, the time delay is presumably caused by the spiralling motion of the protons around the magnetic field and gives an indication of the strength of the field; it corresponds to an order of magnitude of 10^{-4} or 10^{-5} gauss. Second, it is significant that the solar protons, although somewhat delayed by their passage through the plasma cloud, still arrived with relative rapidity and in great numbers; this proves that the magnetic field does in fact have its roots in the flare region, and that the magnetic lines of force connect the earth directly with the sun in an approximately radial configuration.

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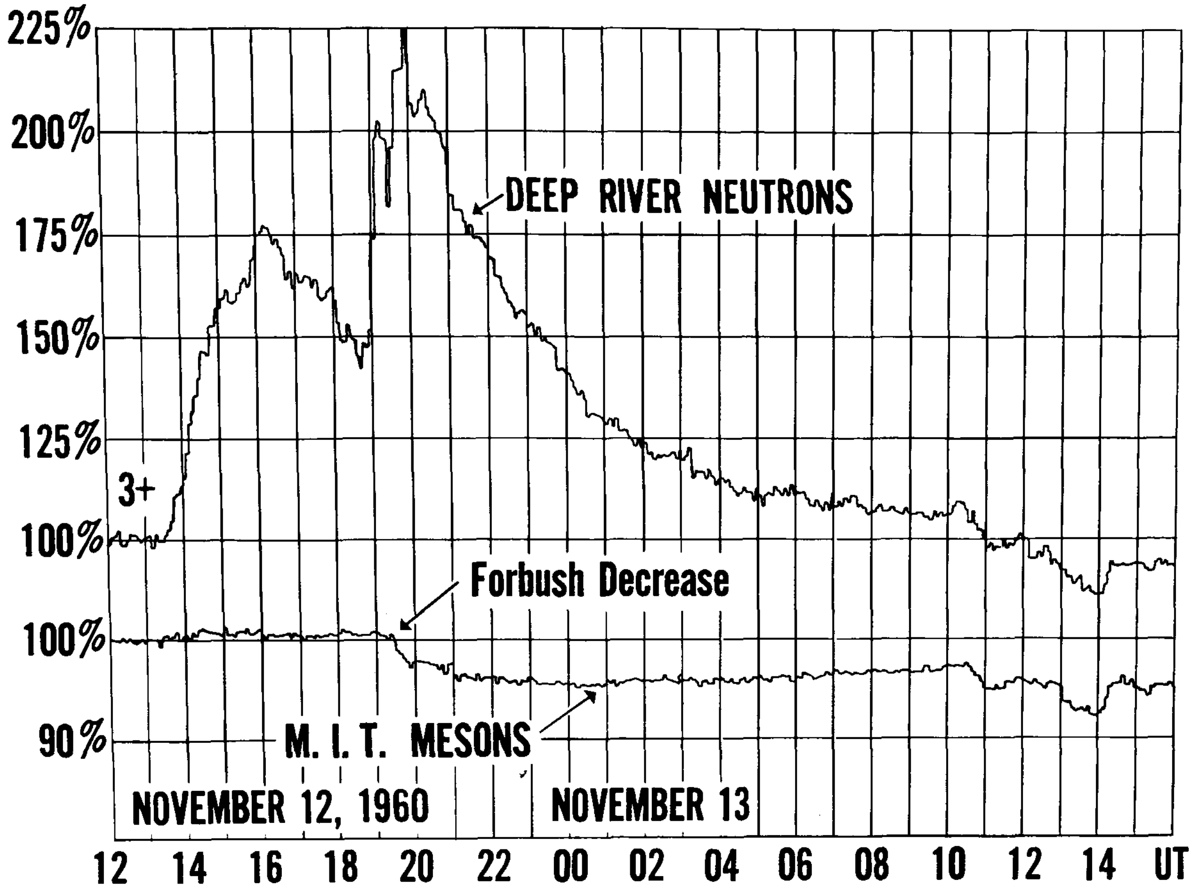


FIGURE 11. Events accompanying the solar flares of November 11–12, 1960 (McCracken, Carmichael, and Steljes).

Simpson comments that the observed transit time of the protons is also consistent with an irregular but very weak field, with the strength of less than one gamma; but there is evidence against this alternative, in that the flare on March 30 was followed by a Forbush decrease signifying the presence of an appreciable magnetic field inside the plasma cloud.

The sequence of these events is shown in figure 10, taken from the report by Simpson, C. Y. Fan, and T. P. Meyer, Enrico Fermi Institute for Nuclear Studies, University of Chicago, which presents at the same time the Pioneer V magnetometer data obtained by Sonett, Coleman, and their collaborators at the Space Technology Laboratory. It shows the Forbush decrease which occurred in space at about the same time it was observed on earth, and also the accompanying changes in the magnetic field.

Thus the event of April 1960 supports the picture that has been developed by demonstrating that when the earth is within the cloud of plasma produced by a flare, there is a direct connection to the site of the flare by magnetic lines of force running back more or less radially to the sun.

It only remains to complete the demonstration by searching for an event in which the earth is initially outside the bottle at the time of emission of a burst of fast solar protons but is subsequently enveloped by the cloud and subjected to the full intensity of bombardment by the bottled protons. Such a case was provided by the event of November 1960. This event included six flares with magnitudes between Class 2 and 3+ in the interval of November 10 and November 15. It was the most violent solar outburst since the great event of February 23, 1956; and as the frequency of occurrence of these flares follows the 11-year sunspot cycle, and we are now well along toward the minimum of sunspot activity expected in 1964, it is probably the last such event to be seen for a number of years. It was therefore an occasion of exceptional importance.

A very illuminating discussion of the November event has been published by Kenneth McCracken of MIT and H. Carmichael and J. F. Steljes of the Deep River Laboratory, Ontario, Canada. The important elements of the sequence are as follows: On November 11, 1960, at 0305 a flare of moderate size occurred which apparently produced no energetic protons, but did eject a substantial cloud of plasma. The arrival of this plasma cloud at the earth was signaled by the onset of a magnetic storm on November 12 at 1846 and a Forbush decrease on November 12 at 1930, both approximately 40 hours after the flare began. This was a relatively slow moving plasma cloud with a velocity of about 500 miles per second.

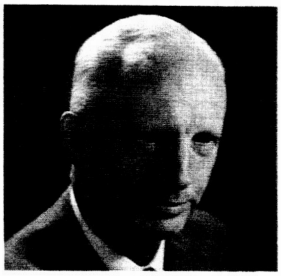
The Forbush decrease appears in the MIT meson detectors as a clearly defined drop in the counting rate, as shown in figure 11. These MIT detectors respond only to very energetic events with primaries in the Bev range or higher, and they can therefore be considered as a true measure of the general cosmic ray intensity. They would not show a response to solar protons in the 100 mev range.

On November 12 at 1325 a very large flare of Class 3+ began and lasted until 1922. This flare produced a burst of energetic solar protons, just as in the case of the second major flare of the April 1960 event. Their arrival at the earth was signaled by an increase in the counting rate of the neutron monitor at Deep River, Canada, starting about 1340 GMT. The Deep River counters respond to neutrons produced by nuclear collisions of the solar protons in the atmosphere, and therefore provide a good indicator of the arrival of these protons. The counting rate at Deep River climbed over a period of a few hours, and then began a slow decline (figure 11, upper curve).

At 1930 GMT, when the general intensity of cosmic rays diminished, signaling the onset of the Forbush decrease, the intensity of the solar protons spurted *upward*, as indicated by the Deep River counter, to a new peak, which it reached in about 1 hour. It then began a slow decline once again.

This otherwise puzzling sequence is clearly explained by the present picture. We need only consider that the protons generated in the second flare were ejected into the cloud of plasma from the first flare, and must have been confined thereafter within this cloud by the magnetic field it contained. As we have noted, such a cloud constitutes a magnetic bottle by virtue of its field; however, the confinement within the bottle need not be perfect, and some protons apparently leaked out and reached the earth to produce the moderate increase detected at Deep River beginning at 1350 GMT.

J. F. Steljes



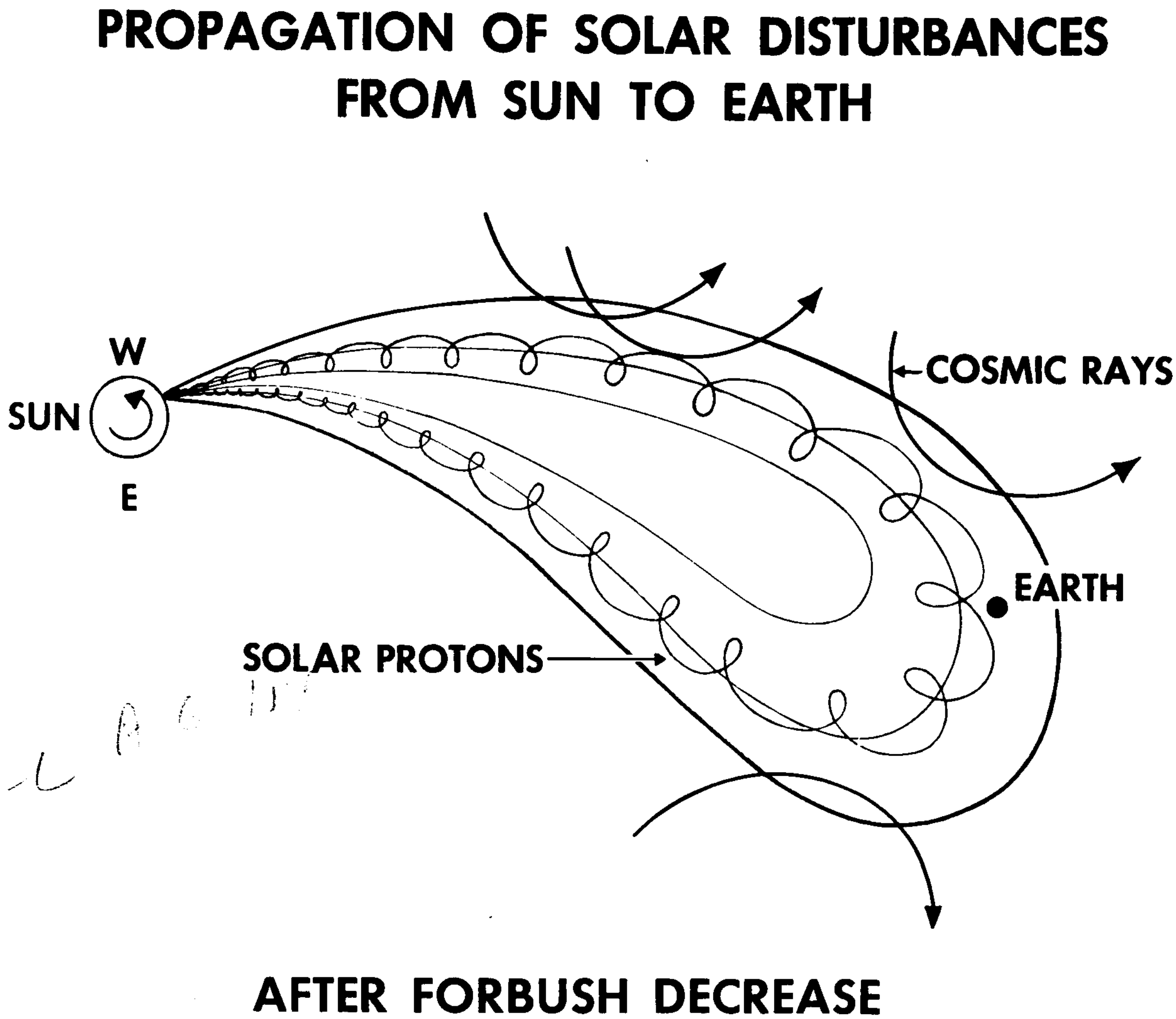
Hugh Carmichael

But at about 1930 GMT the earth was enveloped by the expanding plasma cloud from the first flare, as indicated by the commencement of the magnetic storm and the Forbush decrease at that time. From that point on, the earth was also within the bottle, and subjected to the full intensity of bombardment by the confined protons. This event is marked by the upward spurt in the Deep River counter. Thereafter the bombardment slowly decreased as the bottle protons continued to diffuse out of the cloud and their intensity diminished. Thus in the data from the flares of November 1960, we find further support for the present picture of the development of solar events.

In the preparation of this lecture I had occasion to look over the paper on solar plasma read by Thomas Gold of Cornell at a meeting in Washington nearly 3 years ago. It is an impressive tribute to his physical insight that at that early date and on the basis of very slight evidence he was able to outline all essential elements in the present description of the propagation of solar disturbances.

I should like to say, in concluding this review, that these experiments and theoretical developments may be viewed as filling in gaps in our basic knowledge of our space environment, and providing immediately useful information as well. But they have an additional effect extending beyond the boundaries of space science—the excitement of opening up new areas of research created by the accessibility of the data which rockets and satellites can provide. These new frontiers bring a productive ferment and a vitality and stimulation to all science, which must be placed alongside the specific achievements as one of the most important consequences of experiments in space.

FIGURE 12. Propagation of solar disturbances from sun to earth.



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